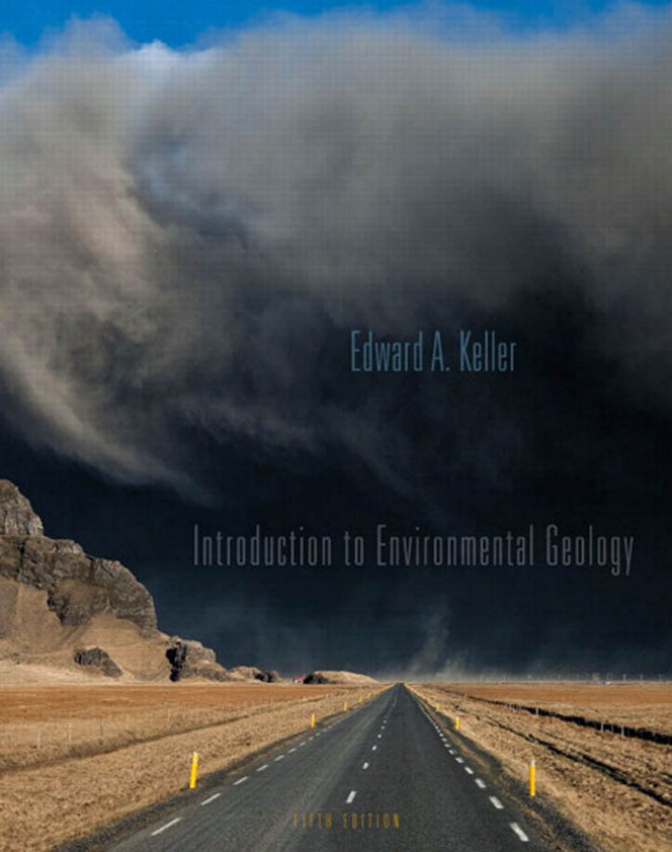


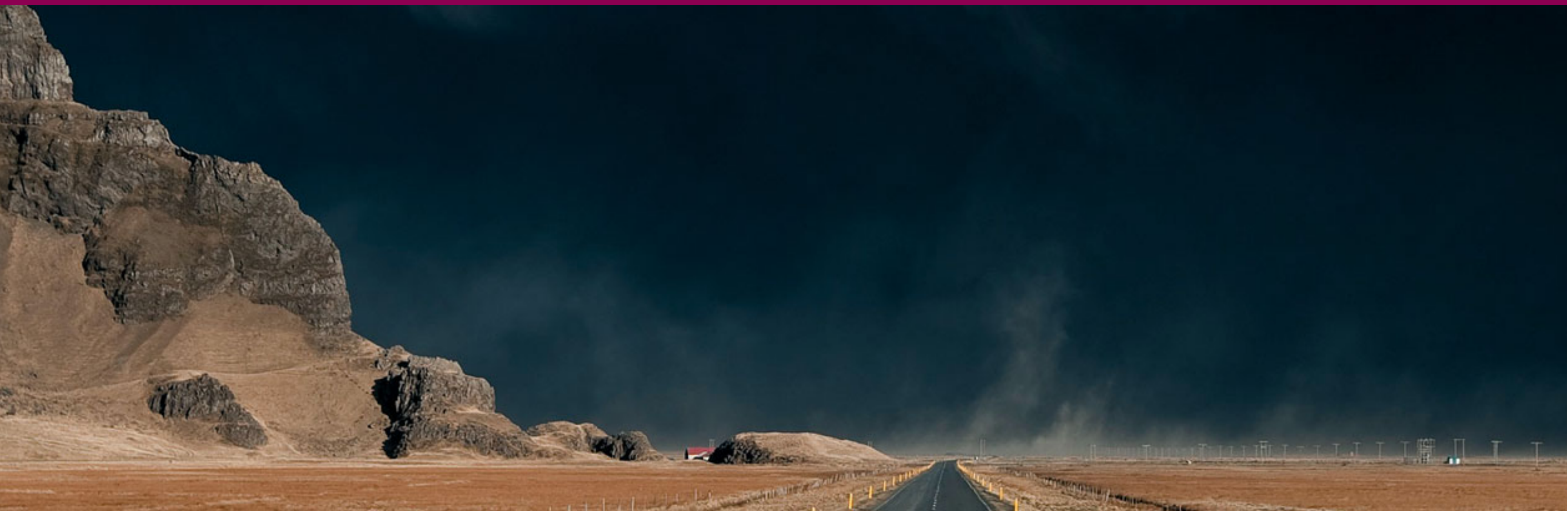
Edward A. Keller

Introduction to Environmental Geology

FIFTH EDITION

This page intentionally left blank

Introduction to Environmental Geology



Edward A. Keller
University of California, Santa Barbara

Fifth Edition

Prentice Hall
Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montréal Toronto
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Library of Congress Cataloging-in-Publication Data

Keller, Edward A., 1942-
Introduction to environmental geology/ Edward A. Keller.–5th ed.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-321-72751-0
ISBN-10: 0-321-72751-7
1. Environmental geology. I. Title.
QE38.K46 2011
550–dc22 2010053127

Acquisitions Editor, Geology: Andrew Dunaway
Marketing Manager: Maureen McLaughlin
Project Editor: Crissy Dudonis
Assistant Editor: Sean Hale
Editorial Assistant: Michelle L. White
Marketing Assistant: Nicola Houston
Managing Editor, Geosciences and Chemistry: Gina M. Cheselka
Project Manager: Wendy Perez
Full Service/Composition: Element, LLC
Production Editor, Full Service: Heidi Allgair
Art Director: Derek Bacchus
Cover and Interior Design: Emily Friel
Senior Technical Art Specialist: Connie Long
Art Project Manager: Ronda Whitson
Art Studio: Spatial Graphics
Photo Research Manager: Elaine Soares/Billy Ray
Photo Researcher: Stacey Stambaugh
Senior Manufacturing and Operations Manager: Nick Sklitsis
Operations Supervisor: Maura Zaldivar
Senior Media Producer: Angela Bernhardt
Media Producer: Ziki Dekel
Associate Media Project Manager: David Chavez
Cover Photo: © Artic-Images/Corbis

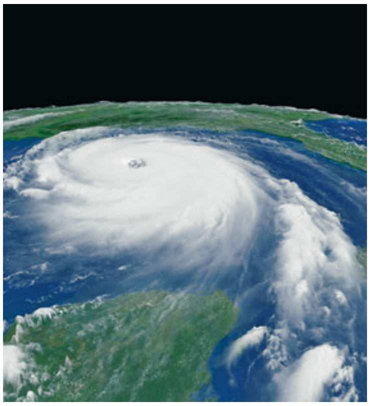
Pearson Prentice Hall
Pearson Education, Inc.
Upper Saddle River, New Jersey 07458

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

ISBN-10: 0-321-72751-7 / ISBN-13: 978-0-321-72751-0
(Student Edition)

Brief Contents

Contents




Long Island Sound
ATLANTIC OCEAN

Preface

The main objective of *Introduction to Environmental Geology*, fifth edition, is to assist students—particularly those who intend to take only a single science course—in gaining an understanding of the interactions between geologic processes, ecological processes, and society. During the first half of the twenty-first century, as the human population increases, the use of resources grows, and changes to the climate occur, many decisions concerning our use of those resources—such as water, soil, air, minerals, energy, and space to live—will determine our standard of living and the quality of our lives and of the broader environment of our home, Earth. Scientific knowledge combined with our values will dictate many important decisions that will have far-reaching consequences for this and future generations. Your charge, as a student, future leader, or informed citizen, is to choose paths of development that are beneficial for people and the environment—that is, the larger community that includes plants, animals, water, and air—in other words, the environment consisting of ecosystems that we and all living things depend upon for our well-being.

Earth's dynamic and changing environment constitutes one of the most compelling and exciting areas of study. Environmental geology involves the application of geologic information to the entire spectrum of interactions between people and the physical environment. During a course in environmental geology, you will develop an understanding of how geology interacts with major environmental problems facing people and society. This is the essence of *Introduction to Environmental Geology*, fifth edition. Our strategy with this text is to:

- Introduce you to the basic concepts and principles of physical and environmental geology, focusing on Earth materials and processes.
- Provide you with sufficient information concerning natural hazards and the geologic environment that you will be a more informed citizen. You will be better prepared to make decisions concerning where you live and how society responds to natural hazards and catastrophes such as earthquakes, volcanic eruptions, and flooding.
- Help you develop an understanding of relationships between natural resources and pollution. We seek, find, and use resources and, as a result, may pollute our environment. Thus, it is important to know how we might minimize pollution problems.
- Help you understand the basic concepts of environmental management as they relate to the geologic environment in areas such as waste management, environmental health, global change, and environmental assessment.

After finishing your course in environmental geology, you will be better prepared to make decisions concerning where you build or buy a home, what resources you choose to utilize, and appropriate environmental actions relevant to society and Earth's ecosystems from a local scale to a global scale.

New to This Edition

This fifth edition benefited greatly from feedback from instructors using the text; most of the changes reflect their thoughtful reviews. One new chapter, on tsunamis (Chapter 7), recognizes important links between earthquakes and marine processes that pose a serious hazard to millions of people living in coastal areas. In addition to this new chapter, new or extensively revised discussions with some quantification include:

- The Wilson Cycle and plate tectonics (Chapter 2)
- Earthquake process and how we determine slip rates on faults (Chapter 6)
- How a simple landslide hazard and factor of safety may be determined (Chapter 10)
- How a beach budget is produced (Chapter 11)
- Evaluation of flooding and water pollution linked to ecosystems (Chapters 13 and 14)
- Extensive revision of energy resources and policy (Chapter 16)
- Global climate change and, in particular, global warming (Chapter 18)
- New capstone chapter (Chapter 19) on environmental health, air pollution, waste management, environmental analysis (impact,

planning, and law), and the central role of sustainability

- Making the Connection: Most chapters contain material that help students "make the connection" between the case histories within the chapter and the Five Fundamental Concepts on which this book is founded.

Five Fundamental Concepts

This book begins with five fundamental concepts of environmental geology. These five concepts were selected and designed to provide a memorable, transportable framework of understanding that you can carry away from the class and use throughout life to make informed choices about your interaction with and effect upon geologic processes:

- **Human population growth:** Population growth is the number-one environmental problem. As population increases, so do our effects and demands on the environment.
- **Sustainability:** Sustainability is the long-term environmental objective of providing for the future of humans and other living things who share the planet.
- **Earth as a system:** The activities of human beings can have important effects on any or all of Earth's systems, often affecting the global environment.
- **Hazardous Earth processes:** Earth's hazardous processes have always occurred and will always occur. Human beings need to recognize the threat of hazards, assess the risk to life and property, and either avoid these hazards or plan accordingly.
- **Scientific knowledge and values:** Scientific inquiries often provide a variety of potential solutions to environmental problems. The solution we choose is a direct reflection of our value system.

These concepts are introduced in the first chapter and then highlighted throughout the text (look for the "Revisiting the Fundamental Concepts" section at the end of each chapter). Also at the end of each chapter, we return to the case history opening the chapter and reconnect to the case history through selected aspects of the fundamental concepts through posing a series of questions. By tying the content to these five principles, the text provides a framework for understanding that will extend beyond the confines of this course and into your everyday life.

Organization

Introduction to Environmental Geology, fifth edition, is well suited to your study of environmental geology, whether you are a geology major or are taking this class as a science elective. I have organized *Introduction to Environmental Geology*, fifth edition, to flow naturally from the introduction of fundamental principles of environmental science and geology, to more specific information concerning how Earth works, to natural processes and hazards, to understanding natural resources and their management, with the objective of minimizing environmental degradation. We end with a detailed discussion of global change, focusing on climate and some important interactions between society and the geologic environment.

Introduction to Environmental Geology, fifth edition, consists of 19 chapters arranged in four parts:

- Part 1 introduces philosophy and fundamental concepts, the structure of Earth and plate tectonics, and the origin and significance of minerals and rocks. Thus, Part 1 presents fundamentals of physical geology, with important environmental information necessary to understand the remainder of the text. Chapter 1 introduces five fundamental concepts of environmental science, with an emphasis on the geologic environment. Chapter 2 discusses the structure of Earth and the important subject of plate tectonics and how our planet works from a geologic perspective. Chapter 3 presents geologic information concerning rocks and minerals necessary for understanding environmental geology problems and solutions to those problems. In Chapter 3, we also introduce some of the fundamental principles of geology, including the law of original horizontality, the law of cross-cutting relationships, the concept of the depositional environment, the concept of the rock cycle, and the principle of magmatic differentiation. Chapter 4 presents basics of ecology with links to geology. An ecosystem includes a community of life and its non-living environment (rock, soil, etc.). The emerging study of geology linked to ecology is exciting and offers many opportunities.

- Part 2 addresses natural hazards, including an introduction to natural hazards (Chapter 5), earthquakes (Chapter 6), tsunami (Chapter 7), volcanic activity (Chapter 8), rivers and flooding (Chapter 9), landslides (Chapter 10), coastal processes (Chapter 11), and impacts of extraterrestrial objects (Chapter 12). The intent is not to provide copious amounts of detailed information concerning these processes but to focus on the basics involved and the environmental concerns of Earth processes and natural hazards.
- Part 3 presents the major resources associated with the geologic environment and the subject of pollution. Important topics include water resources (Chapter 13), water pollution (Chapter 14), mineral resources (Chapter 15), energy resources (Chapter 16), and soils (Chapter 17). The focus is to present the basic principles concerning natural resources and to identify potential environmental problems and solutions.
- Part 4 is concerned with the important topics of global change, environmental management, and relationships between environment and society. Chapter 18 discusses global change with a focus on global warming and stratospheric ozone depletion. Finally, in Chapter 19, which is a capstone for the book, we discuss relationships between environment and society, with topics such as environmental health, air pollution, waste management, land use planning, environmental law, environmental impact analysis, how we may achieve the goal of obtaining environmental sustainability, and how that might change our relationships with our home, Earth.

Features of the Text

This book is sensitive to the study needs of students. Each chapter is clearly structured to help you understand the material and effectively review the major concepts. To help you use the material from the book, each chapter is organized with the following study aids:

- Learning objectives that state clearly what you should be able to do upon completing the chapter.
- Selected features, called *Case History* and *A Closer Look*, are added where appropriate to help you relate topics in the text to the world around you. A case history opens each chapter, and that case history is revisited at the end of the chapter.
- A chapter summary reinforces the major points of the chapter to help you refocus on the important subjects.
- The foundations of environmental geology are presented in Chapters 1 through 4, and Chapters 5 through 19 contain discussions that revisit the five fundamental principles in terms of the material presented in the chapter.
- Detailed references are supplied at the end of the text to provide additional readings and to give credit to the scholars who did the research reported in the chapter.
- Key terms are presented at the end of each chapter. These will help you identify the important concepts and terminology necessary to better understand the chapter.
- Review questions help with your review of important subject matter.
- Critical thinking questions stimulate you to think about some of the important issues in the chapters and try to relate them to your life and society.

The appendices in *Introduction to Environmental Geology*, fifth edition, are intended to add additional information useful in helping you understand some of the applied aspects of environmental geology. This information may be most useful in supplementing laboratory exercises and field exercises in which you may participate. Specific topics include:

- Identification of rocks and minerals, with accompanying tables and suggestions
- Introduction to topographic and geologic maps with specific information concerning how to read topographic maps, construct topographic profiles, and understand geologic maps
- Introduction to digital elevation models (DEMs), LiDAR, and Global Positioning System (GPS) instrumentation
- Discussion of how geologists determine and interpret geologic time
- Darcy's Law, with example of how we use it to solve groundwater problems
- A glossary of terms used in the field of environmental geology

The New Instructional Package

Pearson Prentice Hall has assembled a greatly improved resource package for *Introduction to Environmental Geology*, fifth edition.

For the Instructor

Instructor's Resource Center on DVD All digital resources can be found in one, well-organized, easy-to-access place. The Instructor's Resource Center on DVD includes the following:

- **Art:** All of the textbook images are provided as JPEGs, PDFs, and PowerPoint® presentations.
- **Lecture Outlines:** This set averages 35 slides per chapter and includes customizable lecture outlines with supporting art that can be customized to fit instructors' lecture requirements.
- **Clicker Questions:** To be used in conjunction with your Personal Response System, these PowerPoint presentations give a professor a chance to query students immediately on some of the main elements and themes of each chapter.

This Instructor Resource content is also available completely online via the Instructor Resources section of www.mygeoscienceplace.com and www.pearsonhighered.com/irc.

Instructor's Resource Materials The instructor's manual, which is available via download, provides chapter outlines and objectives, classroom discussion topics, and answers to the end-of-chapter questions in the textbook. The test bank includes nearly 1,000 multiple-choice, true/false, and short-answer test questions based on the text to gauge students' knowledge.

For the Student

MyGeoscienceplace New media on the premium website, found at www.mygeoscienceplace.com, includes assignable, assessable animations from the *Geoscience Animation Library* correlated directly to the text. The site also contains assignable chapter quizzes, interactive flashcards, a glossary, web links, and RSS feeds providing students with articles about current geologic events and data from trusted sites and sources, such as the United States Geological Survey (USGS). This site will also now host the online version of *Hazard City*.

***Hazard City: Assignments in Applied Geology*, fourth edition** Found on the premium website, *Hazard City* provides instructors meaningful, easy-to-assign, and easy-to-grade assignments for students. Based on the fictional town of Hazard City, the assignments put students in the role of a practicing geologist—gathering and analyzing real data, evaluating risks, and making assessments and recommendations. *Hazard City* provides the following resources and benefits:

- **Substantial critical thinking assignments:** Each activity takes 30–90 minutes. The activities require students to gather and analyze real data, participate in real issues, encounter uncertainty, and make decisions.
- **New assessment questions:** Assignable, assessable multiple-choice questions have been added to each *Hazard City* assignment. The questions engage students in higher-order thinking to apply the concepts and processes learned in the assignments to the broader world in different contexts.
- **Student flexibility for submitting answers:** Using downloadable worksheets, students can print out, complete, and submit their answers to the instructor. Students can also answer assignable multiple-choice questions directly from the premium website that are computer graded and feed to a course grade book.
- **Thoroughly class tested:** All activities have been refined through testing in both the traditional and online classroom.

Hazard City provides the following activities:

- **Map Reading:** This activity builds map-reading skills and gives students the confidence they need to solve map-based problems in later assignments.
- **Groundwater Contamination:** Students use field and laboratory data to prepare a contour map of the water table, determine the direction of groundwater flow, and map a contaminated area.
- **Volcanic Hazard Assessment:** Students research volcanic hazards, collect field information, and make decisions to determine the potential impact of a volcanic eruption on different parts of *Hazard City*.

- **Landslide Hazard Assessment:** Students research the factors that determine landslide hazard at five construction sites and make recommendations for development.
- **Earthquake Damage Assessment:** Students research the effects of earthquakes on buildings, explore Hazard City, and determine how many people need emergency housing, given an earthquake of specific intensity.
- **Flood Insurance Rate Maps:** Flood insurance premiums are estimated using a flood insurance rate map, insurance tables, and site characteristics.
- **Snowpack Monitoring:** Students utilize climatic data to estimate variables that are key to flood control and water supply management.
- **Coal Property Evaluation:** The potential value of a mineral property is estimated by learning about mining and property evaluation and then applying that knowledge in a resource calculation.
- **Landfill Siting:** Students use maps and geologic data to determine whether any of five proposed sites meet the requirements of the state administrative code for landfill siting.
- **Shoreline Property Assessment:** Students visit four related waterfront building sites—some developed and some not—and analyze the risk each faces due to shoreline erosion processes.
- **Tsunami/Storm Surge:** Students learn about the causes and effects of tsunamis and storm surge, and then they develop a hazard assessment response in case of inundation by water.

Acknowledgments

Successful completion of this book was greatly facilitated by the assistance of many individuals, companies, and agencies. In particular, I am indebted to the U.S. Geological Survey and its excellent environmental programs and publications. To the Internet as a tremendous tool to quickly contact people and organizations doing environmental work. To authors of papers cited in this book, I offer my thanks and appreciation for their contributions; without their work, this book could not have been written. I must also thank the thoughtful people who dedicated valuable time completing reviews of chapters or the entire book. Their efforts have greatly contributed to this work. I wish to thank Joseph Allen, Concord University; Scott Brame, Clemson University; John Bratton, Stonehill College; Eleanor J. Camann, Georgia Southern University; Elizabeth Catlos, Oklahoma State University; Susan Celestian, Rio Salado College; Tim Clarey, Delta College; Raymond M. Coveney, Jr., University of Missouri; Ken Griffith, Tarrant County Community College–Northwest; William M. Harris, University of St. Thomas; Carolyn Hudson, University of South Carolina; Jennifer Johansen, Alverno College; Michael Krol, Bridgewater State College; Dan Leavell, Ohio State University–Newark; Paul Lowrey, Northwest Arkansas Community College; Stephen MacAvoy, American University; J. Barry Maynard, University of Cincinnati; Stephen R. Newkirk, University of Memphis; Michael Phillips, Illinois Valley Community College; Jeanette Pope, DePauw University; Conrad Shiba, Centre College; Christiane Stidham, Stony Brook University; Hongbing Sun, Rider University; Kevin Svitana, Otterbein College; Anna Tary, Boston University; Christopher Thomas, North Carolina School of Science and Mathematics; Cynthia Venn, Bloomsburg University; and Kenneth Windom, Iowa State University.

Special thanks go to Tanya Atwater, William Wise, and Frank Spera for their assistance in preparing the chapters on plate tectonics, minerals and rocks, and impacts, respectively. I greatly appreciate the review of the new chapter on geology and ecology by Carla D'Antonio, who provided important information and advice on basic principles of ecology and ecological restoration.

I am particularly indebted to my editors at Prentice Hall. Special thanks go to my geology editor, Andrew Dunaway, and project editor, Crissy Dudonis, whose enthusiasm, intelligence, encouragement, ideas, and creativity made this book possible. Thanks to Heidi Allgair and Kitty Wilson for editing and manuscript planning. I greatly appreciate the assistance of Maureen McLaughlin, marketing manager. I also appreciate the efforts of Wendy Perez, production editor, and Stacey Stambaugh, photo editor. Art was rendered by Spatial Graphics. Thanks to Derek Bacchus, art director, and Emily Friel, interior designer, for their work in updating the interior and cover design for this new edition. I appreciate the encouragement and support from my wife, Valery, who assisted by pointing out ways to improve the content and presentation.

Edward A. Keller
Santa Barbara, California

About Our Sustainability Initiatives

This book is carefully crafted to minimize environmental impact. The materials used to manufacture this book originated from sources committed to responsible forestry practices.

The paper is Forest Stewardship Council (FSC) certified. The printing, binding, cover, and paper come from facilities that minimize waste, energy consumption, and the use of harmful chemicals.

Pearson closes the loop by recycling every out-of-date text returned to our warehouse. We pulp the books, and the pulp is used to produce items such as paper coffee cups and shopping bags. In addition, Pearson aims to become the first climate neutral educational publishing company.

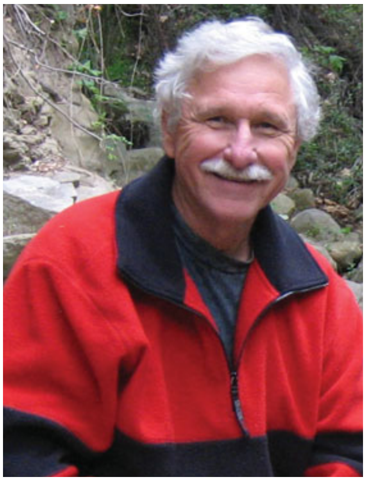
The future holds great promise for reducing our impact on Earth's environment, and Pearson is proud to be leading the way. We strive to publish the best books with the most up-to-date and accurate content, and to do so in ways that minimize our impact on Earth.

FSC
www.fsc.org
MIX
Paper from responsible sources
FSC® C005928

This book is dedicated to the next generation of people on Earth who will, more than others before them, by necessity make many important decisions about population growth, global change, energy use, and land use that will be so important in the next few decades. It appears that environmental problems will need to be very seriously addressed very soon if we wish to sustain Earth as we in the present generation know it.

About the Author

Edward A. Keller



Ed Keller is a professor, researcher, writer, and, most importantly, mentor and teacher to undergraduate and graduate students. Currently, Dr. Keller's students are working on earthquake hazards, tectonic geomorphology of active flooding, the role of wildfire in landscape development, geologic and hydrologic that control the formation of pools that are important habitat to endangered southern steelhead trout, flood hazards, the role of the invasive plant *Arundo donax* (which looks like bamboo) on stream form and process in southern California, and the origin of small coastal lagoons in southern California.

Ed was born and raised in southern California. He holds a bachelor's degree in Geology and Mathematics from California State University at Fresno, a master's degree in Geology from the University of California at Davis, and a Ph.D. in Geology from Purdue University. While pursuing his Ph.D. in Geology from Purdue University in 1973, Ed wrote part of the first edition of *Environmental Geology* (now in the ninth edition). The text soon became a foundation of the environmental geology curriculum.

Ed joined the faculty of the University of California at Santa Barbara in 1976 and has been there since, serving multiple times as the chair of both the Environmental Studies and Hydrologic Science programs. In that time, he has been an author of more than 100 articles, including seminal works on fluvial processes and tectonic geomorphology. Ed's academic honors include the Don J. Easterbrook Distinguished Scientist Award, Geological Society of America (2004), the Quatercentenary Fellowship from Cambridge University, England (2000), two Outstanding Alumnus Awards from Purdue University (1994, 1996), a Distinguished Alumnus Award from California State University at Fresno (1998), and the Outstanding Outreach Award from the Southern California Earthquake Center (1999). Ed is a fellow of the Geological Society of America.

Ed and his wife, Valery, who brings clarity to his writing, love walks on the beach at sunset and when the night herons guard moonlight sand at Arroyo Burro Beach in Santa Barbara. Walking beaches in the moonlight inspired the following.

This page intentionally left blank

We Are Children of the Pleistocene

Whether it is clear to us or not we are a children of the Pleistocene
Our genes gives us away
Nearly invariant over more than one hundred thousand years of deep time

We remain connected to nature in many fascinating and mysterious ways

Vision connects us with our universe
Children playing
Star light
Sunrise and set

Natural sounds make us feel alive
Music of frogs at night flow of stream over pebbles on streambed
Swish of water on the beach
Rustle of leaves from wind crunch of grass from foot steep
Howl of wolf
Scream of mountain lion
Shriek of hawk
Rattle of snake
Scratch of predator claw on rock

Quiet places comfort us deep valleys
Forest floor
Snow covered wild land
Silence of night

Smells awaken our senses
Wet forest soil following rain
Salty air kicked up by waves
Morning mist
Fresh barriers
Our loved ones
We are more at ease in nature than with the horn screech of tires and jackhammer

Fire provokes an image of contentment safety and community
We dance play instruments sing and tell stories about other tribes and predators perhaps another football team around a fire as we always have

Hike with a group during the day we spread out
At night hike and we group together with flashlights on
We feel safer when closer together

We walk our property
Marking territory with signs or acts

We seek romantic natural places such as meadows beaches or forest to be with our mate at intimate times

When we are not connected to nature we deprive ourselves and our children of our heritage and our souls suffer
We are a children of the Pleistocene
Embrace our heritage and our souls sing

E. A. Keller
First line inspired by a line ("You are a child of the universe . . .") in a poem by Max Ehrmann. (1927). "Desiderata: A Poem for a Way of Life," Terre Haute, Indiana.

This page intentionally left blank

Part 1

Foundations of Environmental Geology

The objective of Part 1 is to present the five fundamental principles of environmental geology and the important concepts necessary to understand the rest of the text. Of particular importance are (1) the fundamental concepts of environmental science, emphasizing the geologic environment; (2) information about the structure of Earth and, from a plate tectonics perspective, how our planet works; (3) geologic information concerning rocks and minerals necessary to understand environmental geology problems and solutions to those problems; and (4) an understanding of linkages between geologic processes and the living world.

Chapter 1 opens with a definition and discussion of environmental geology, followed by a short history of the universe and the origin of Earth. Of particular importance is the concept of geologic time, which is critical in evaluating the role of geologic processes and human interaction in the environment. Five fundamental concepts are introduced: human population growth, sustainability, Earth as a system, hazardous Earth processes, and scientific knowledge and values. These are revisited throughout the text. Chapter 2 presents a brief discussion of the internal structure of Earth and a rather lengthy treatment of plate tectonics. Over periods of several tens of millions of years, the positions of the continents and the development of mountain ranges and ocean basins have dramatically changed our global environment. The patterns of ocean currents, global climate, and the distribution of living things on Earth are all, in part, a function of the processes that have constructed and maintained continents and ocean basins over geologic time.

Minerals and rocks and how they form in geologic environments are the subjects of Chapter 3. Minerals and rocks provide basic resources that our society depends on for materials to construct our homes, factories, and other structures; to manufacture airplanes, trains, cars, buses, and trucks that move people and goods around the globe; and to maintain our industrial economy, including everything from computers to eating utensils. The study of minerals and rocks aids in our general understanding of Earth processes at local, regional, and global levels. This knowledge is particularly important in understanding hazardous processes, including landslides and volcanic eruptions, in which properties of the rocks are intimately related to the processes and potential effects on human society.

Geology and ecology and the many links between them are presented in Chapter 4. An ecosystem includes the nonliving environment, which is the geologic environment. In addition, the living part of an ecosystem (i.e., a community of organisms) has many important feedback cycles and links to important landscape and geologic processes. Chapter 4 presents some basics of ecology for geologists and emphasizes their relationship to environmental geology.

Damage to buildings from the 2010 earthquake in Haiti. *(Ideal Stock/Alamy)*

1

Philosophy and Fundamental Concepts

Learning Objectives

In this chapter, we discuss and define *geology* and *environmental geology*, focusing on aspects of culture and society that are particularly significant to environmental awareness. We present some basic concepts of environmental science that provide the philosophical framework of this book. After reading this chapter, you should be prepared to discuss the following:

- **Geology and environmental geology as a science**
- **Increasing human population as the number-one environmental problem**
- **The concept of sustainability and important factors related to the environmental crisis**
- **Earth as a system and changes in systems**
- **The concepts of environmental unity and uniformitarianism and why they are important to environmental geology**
- **Hazardous Earth processes**
- **Scientific knowledge and values**
- **The scientific method**
- **Geologic time and its significance**
- **The precautionary principle**
- **Why solving environmental problems can be difficult**

Case History

Caribbean Island of Hispaniola: Story of History, People, Environmental Damage, and Earthquake

When we study the history of the landscape or people through time, we often employ a scientific method different from that used in laboratory experiments with quantitative manipulation of variables to test hypotheses (i.e., assumed answers to questions). We cannot manipulate the past, and, as a result, we sometimes use comparative studies that have the objective of observing and describing the history of an area and making inferences within a larger framework. This may involve studying the geologic and anthropologic record to make comparisons. This approach can be a fruitful technique in the historical sciences, including geology, ecology, hydrology, and environmental science. One of the research tools is the application of uniformitarianism which states that if we study processes operating today, we can say something about what happened in the past. We may also study the prehistoric and historic record to make inferences about what future changes may occur.[1]

The island of Hispaniola offers an opportunity for comparative research and the evaluation of two countries that are side by side. The eastern two-thirds of the island is the site of what is today the Dominican Republic, and the western one-third of the island is the country Haiti. Both countries share the island, but there are significant differences between them. For example, in the Dominican Republic there is a central area that is a good place for agriculture, and the eastern end of the island receives more rainfall than does the western end. Haiti has more rugged topography, steeper slopes, and less rainfall, and you might expect that it has natural processes working more against it than does the Dominican Republic. This certainly is the case today, but it has not always been so. Earlier in their history, soon after independence, Haiti was far richer than the Dominican Republic; however, there has been a reversal of fortunes, and today Haiti is the poorest country in the Western Hemisphere and one of the poorest in the world. The differences between the Dominican Republic and Haiti are easily seen by examining high-altitude aerial photographs which reveal that the Dominican Republic has a green, forest-covered landscape, compared to the much more desolate, dryer-looking landscape to the east that is Haiti (**Figure 1.1**).[1]

Comparisons of Haiti with the Dominican Republic in terms of size, population, gross domestic product per person, and several other variables are shown in **Table 1.1** (page 6), along with comparative data for Cuba and Puerto Rico. In Haiti, the median age of the population (i.e., that age where 50 percent are younger) is 18, compared to 24 for the Dominican Republic; life expectancy in Haiti is 60 years, compared to 72 in the Dominican Republic; and, most importantly, the forest cover of Haiti is 3.8 percent, compared to 28.4 percent in the Dominican Republic. The percentage of forest cover is much lower for Haiti than for the other Caribbean islands shown in Table 1.1. The annual income for the average Haitian person is only about one-fourth that of the Dominican Republic, half of that for Cuba, and a small percentage of that for Puerto Rico. Also shown in Table 1.1 are the major environmental issues associated with the four islands. Haiti stands out from the other countries because of its extensive deforestation and serious soil erosion problem, both of which are linked to an inadequate and unsafe water supply for the people. As a result, Haiti is nearly a failed state. The government is not able to provide its people with the basics for an adequate life. This situation is unique among the other Caribbean islands.[1,2]

Historians and other scientists have studied the differences between Haiti and the Dominican Republic for a number of years. There is general agreement that many of the differences result from the different colonial histories of the two countries. The people of Haiti went through a bloody revolution with France, gaining their freedom in 1804. Haiti at the time of French rule was prosperous, but it was a slave state with a high population density. Following the bloody revolution when the French were defeated, the Haitian people mistrusted Europeans to such an extent that trade with other countries was much reduced. Furthermore, they had a language and dialect spoken only in Haiti, so there were communication problems with the rest of the world. To complicate matters, Western countries were reluctant to

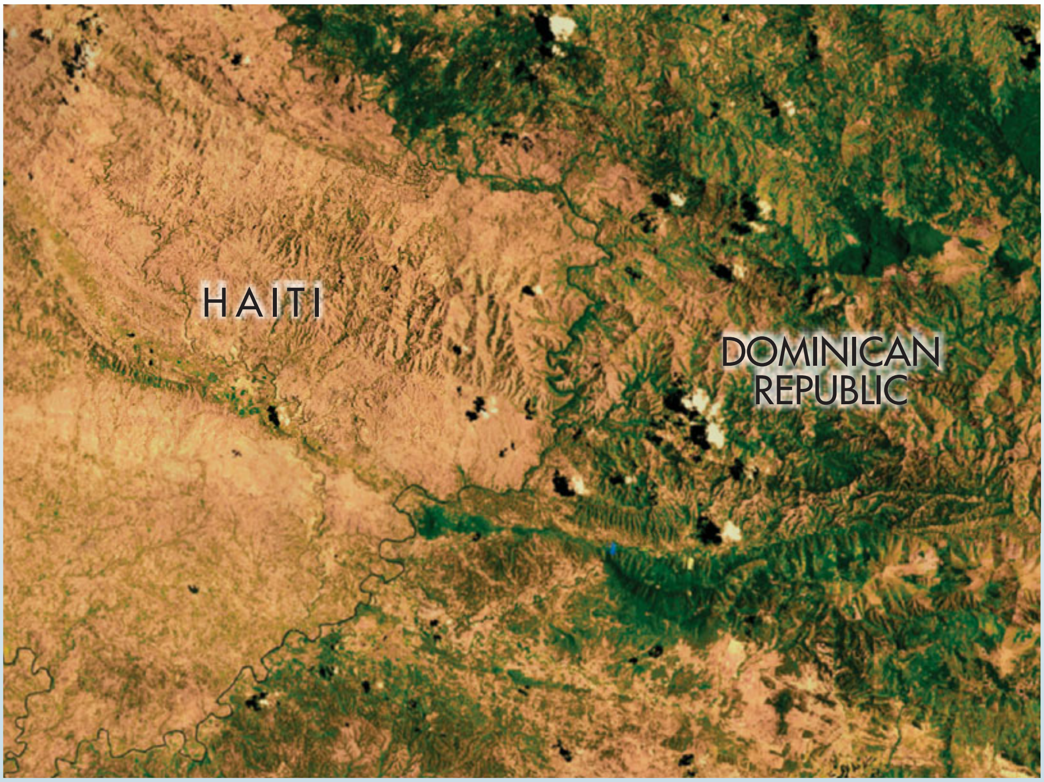


FIGURE 1.1 The border between Haiti and the Dominican Republic is clearly visible as Haiti has experienced massive deforestation and soil erosion. *(Goddard Space Flight Center/NASA)*

deal with a country that had gone through a bloody revolution and overthrown slavery as early as 1804. Even so, following the revolution, Haiti was relatively wealthy and did well for a while. However, eventually, political, social, and economic forces led to a downward spiral that resulted in Haiti becoming the poorest country in the Western Hemisphere. In the Dominican Republic, the path to independence was a much different story. Spain was wealthy in terms of its colonies and wasn't particularly interested in the Dominican Republic; it was more interested in finding gold and other things than in agriculture. As a result, periods of independence for the Dominican Republic fluctuated on and off until, finally, the Spanish just walked away. The Dominican people were left with the Spanish language, a dominant language of the time,[1] and good contacts with European people and, so, were able to be effective in the development of trade and commerce with the rest of the world.

Later in their histories, absolute dictators ruled both countries—but one of the dictators in the Dominican Republic was interested in preserving forests for sustainable timber harvesting in order to increase the money in his own accounts. For this and other reasons, the Dominican Republic today has retained much of its forest cover and has a good deal of land in national parks. On the other hand, when the French were getting ready to leave, they began the deforestation of Haiti by taking a lot of timber with them to Europe; during the period following independence, that deforestation continued at an accelerating pace. Trees were unable to regenerate effectively, due to Haiti's lesser amounts of rainfall, and extensive soil erosion occurred. Today, Haiti is virtually denuded of forests and has a seriously high erosion rate that favors landsliding and other problems related to storms from the Caribbean.[1,2]

The population of Haiti has grown, as has that of the Dominican Republic. However, in Haiti, the high density of people living in degraded land areas has led to a situation in which the people cannot adequately support themselves on their own land, and, as a result, they have become dependent upon importing food and other commodities necessary for life. Furthermore, because the country is so poor, the government has been unable to ensure that adequate building construction codes have been implemented. As a result, when a large earthquake struck in 2010, many government and private buildings collapsed, and the number of deaths was inordinately high. More than 1 million people were displaced when about 190,000 homes were destroyed or damaged. A similar earthquake in the

TABLE 1.1 Comparison of Haiti and the Dominican Republic on the Island of Hispaniola with Puerto Rico and Cuba

Country	Approximate Area (km^2)	Population (millions)	Median Age (years)	Population Growth Rate (percent)	Life Expectancy (years)	Population Density (persons per km^2)	Forest Cover (percent)	Gross Domestic Product per Person ($)	Main Environmental Issues (highly generalized)
Haiti	27,800 (about the size of Maryland)	8.1	18	2.26	60	295	3.8	1,600	Extensive deforestation; serious soil erosion; inadequate safe water supply
Dominican Republic	48,700 (about two times the size of Vermont)	9.0	24	1.29	72	185	28.4	6,500	Water shortages; eroding soils; coral reef damage; deforestation
Puerto Rico	9,100 (about two times the size of Rhode Island)	3.9	34	0.047	79	437	46.0	18,500	Erosion; occasional drought with water shortages
Cuba	110,900 (about the size of Tennessee)	11.3	35	0.33	77	102	24.7	3,300	Loss of biodiversity; pollution; deforestation

Data from the United Nations and http://rainforests.mongabay.com.

United States probably would have produced a few dozen deaths, not over 200,000. In this sense, Haiti's earthquake of 2010, which nearly destroyed the country (one-third of the population was affected), can be considered a human-made disaster.[3,4] One year after the earthquake, most of the displaced people were still living in temporary housing (often tents; see **Figure 1.2**), with too little sanitation, food, and clean water. They remained vulnerable to further hazards from violent storms that periodically strike the region. Most of the earthquake rubble from the destroyed buildings had not been cleared.

In summary, Haiti is an example of what can happen when environmental degradation linked to high human population, degraded water and soil resources, and inadequate infrastructure result in extreme poverty and loss of control of the government in the country. Controlling, limiting, and minimizing adjunct poverty is an important goal for the future of the people of the world if peace and security are to be obtained.

FIGURE 1.2 Temporary housing in Haiti following the 2010 earthquake *(Claudiad/iStockphoto)*

1.1 Introduction to Environmental Geology

Everything has a beginning and an end. Our Earth began about 4.6 billion years ago, when a cloud of interstellar gas known as a solar nebula collapsed, forming protostars and planetary systems (see A Closer Look: Earth's Place in Space). Life on Earth began about 3.5 billion years ago, and, since then, multitudes of diverse organisms have emerged, prospered, and died out, leaving only fossils to mark their place in Earth's history. Just a few million years ago, our ancestors set the stage for the present dominance of the human species. As certainly as our Sun will die, we too will eventually disappear. Viewed in terms of billions of years, our role in Earth's history may be insignificant, but, for those of us now living and for our children and theirs, our impact on the environment is significant indeed.

Geologically speaking, we have been here for a very short time. Dinosaurs, for example, ruled the land for more than 100 million years. Although we do not know how long our own reign will be, the fossil record suggests that all species eventually become extinct. How will the history of our own species unfold, and who will write it? Our hope is to leave something more than some fossils that mark a brief time when *Homo sapiens* flourished. Hopefully, as we evolve we will continue to become more environmentally aware and find ways to live in harmony with our planet.

Geology is the science of processes related to the composition, structure, and history of Earth and its life. Geology is an interdisciplinary science, relying on aspects of chemistry (composition of Earth's materials), physics (natural laws), and biology (understanding of life-forms).

Environmental geology is applied geology. Specifically, it is the use of geologic information to help us solve conflicts in land use, to minimize environmental degradation, and to maximize the beneficial results of using our natural and modified environments. The application of geology to these problems includes the study of the following (**Figure 1.3**):

1. Earth materials, such as minerals, rocks, and soils, to determine how they form, their potential use as resources or waste disposal sites, and their effects on human health

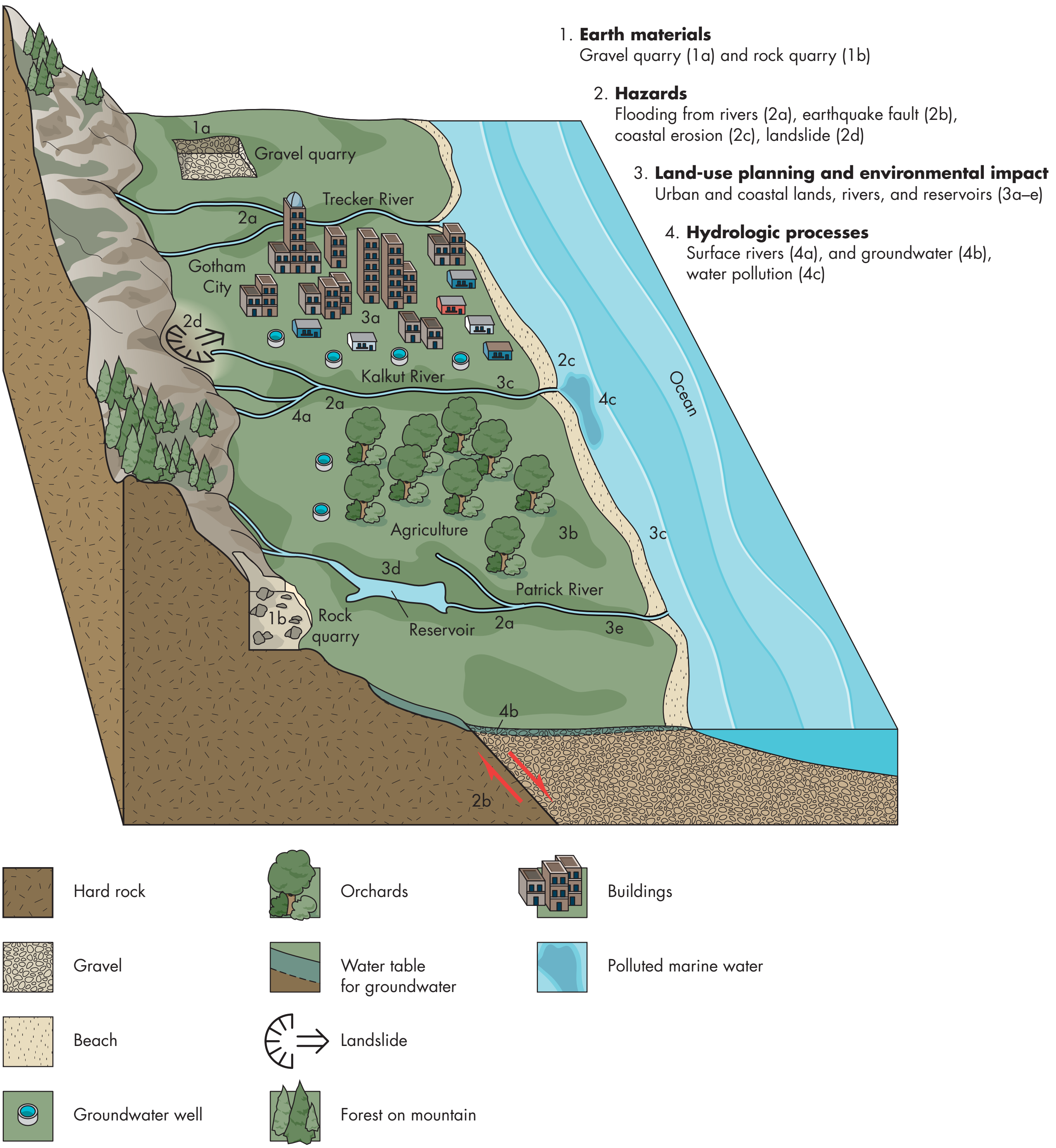


FIGURE 1.3 Components of environmental geology Idealized diagram illustrating four main areas of study for environmental geology. Geologic processes encompass all four areas. These offer employment opportunities for geologists, engineers, and hydrologists.

A Closer Look

Earth's Place in Space

The famous geologist Preston Cloud wrote:

> Born from the wreckage of stars, compressed to a solid state by the force of its own gravity, mobilized by the heat of gravity and radioactivity, clothed in its filmy garments of air and water by the hot breath of volcanoes, shaped and mineralized by 4.6 billion years of crustal evolution, warmed and peopled by the Sun, this resilient but finite globe is all our species has to sustain it forever.[5]

In this short, eloquent statement, Cloud takes us from the origin of Earth to the concept of sustainability that today is at the forefront of thinking about the environment and our future.

We Have a Right to Be Here. The place of humanity in the universe is stated well in the *Desiderata:* "You are a child of the universe, no less than the trees and the stars; you have the right to be here. And whether or not it is clear to you, no doubt the universe is unfolding as it should."[6] To some, this might sound a little out of place in science, but, as emphasized further by Cloud, people can never escape the fact that we are one piece of the biosphere, and, although we stand high in it, we are not above it.[5]

Origin of the Universe. Figure 1.A presents an idealized view of the history of the universe, with an emphasis on the origin of our solar system and Earth. Scientists studying the stars and the origin of the universe believe that, about 12 billion years ago, there was a giant explosion known as the *big bang*. This explosion produced the atomic particles that later formed galaxies, stars, and planets. It is believed that, about 7 billion years ago, one of the first generations of giant stars experienced a tremendous explosion known as a *supernova*. This released huge amounts of energy, producing a solar nebula, which is thought to be a spinning cloud of dust and gas. The solar nebula condensed as a result of gravitational processes, and our Sun formed at the center, but some of the particles may have been trapped in solar orbits as rings, similar to those we observe around the planet Saturn. The density of particles in individual rings was evidently not constant, so gravitational attraction from the largest density of particles in the rings attracted others until they collapsed into the planetary system we have today. Thus, the early history of planet Earth, as well as that of the other planets in our solar system, was characterized by the intense bombardment of meteorites. This bombardment was associated with accretionary processes—that is, the amalgamation of various-sized particles, from dust to meteorites, stony asteroids, and ice-rich comets many kilometers in diameter—that resulted in the formation of Earth about 4.6 billion years ago.[5,7] This is the part of Earth's history that Cloud refers to when he states that Earth was born from the wreckage of stars and compressed to a solid state by the force of its own gravity. Heat generated deep within Earth, along with gravitational settling of heavier elements, such as iron, helped differentiate the planet into the layered structure we see today (see Chapter 2).

Origin of Atmosphere and Water on Earth. Water from ice-cored comets and outgassing, or the release of gases, such as carbon dioxide and water vapor from volcanoes and other processes, produced Earth's early atmosphere and water. About 3.5 billion years ago, the first primitive life-forms appeared on Earth in an oxygen-deficient environment. Some of those primitive organisms began producing oxygen through photosynthesis, which profoundly affected Earth's atmosphere. Early primitive, oxygen-producing life probably lived in the ocean, protected from the Sun's ultraviolet radiation. However, as the atmosphere evolved and oxygen increased, an ozone layer was produced in the atmosphere that shielded Earth from harmful radiation. Plants evolved that colonized the land surface, producing forests, meadows, fields, and other environments that made possible the evolution of animal life on the land.[5]

The spiral of life generalized in Figure 1.A delineates evolution as life changed from simple to complex over several billion years of Earth's history. The names of the eras, periods, and epochs that geologists use to divide **geologic time** are labeled with their range in millions or billions of years from the present (Table 1.2). If you go on to study geology, they will become as familiar to you as the months of the year. The boundaries between eras, periods, and epochs

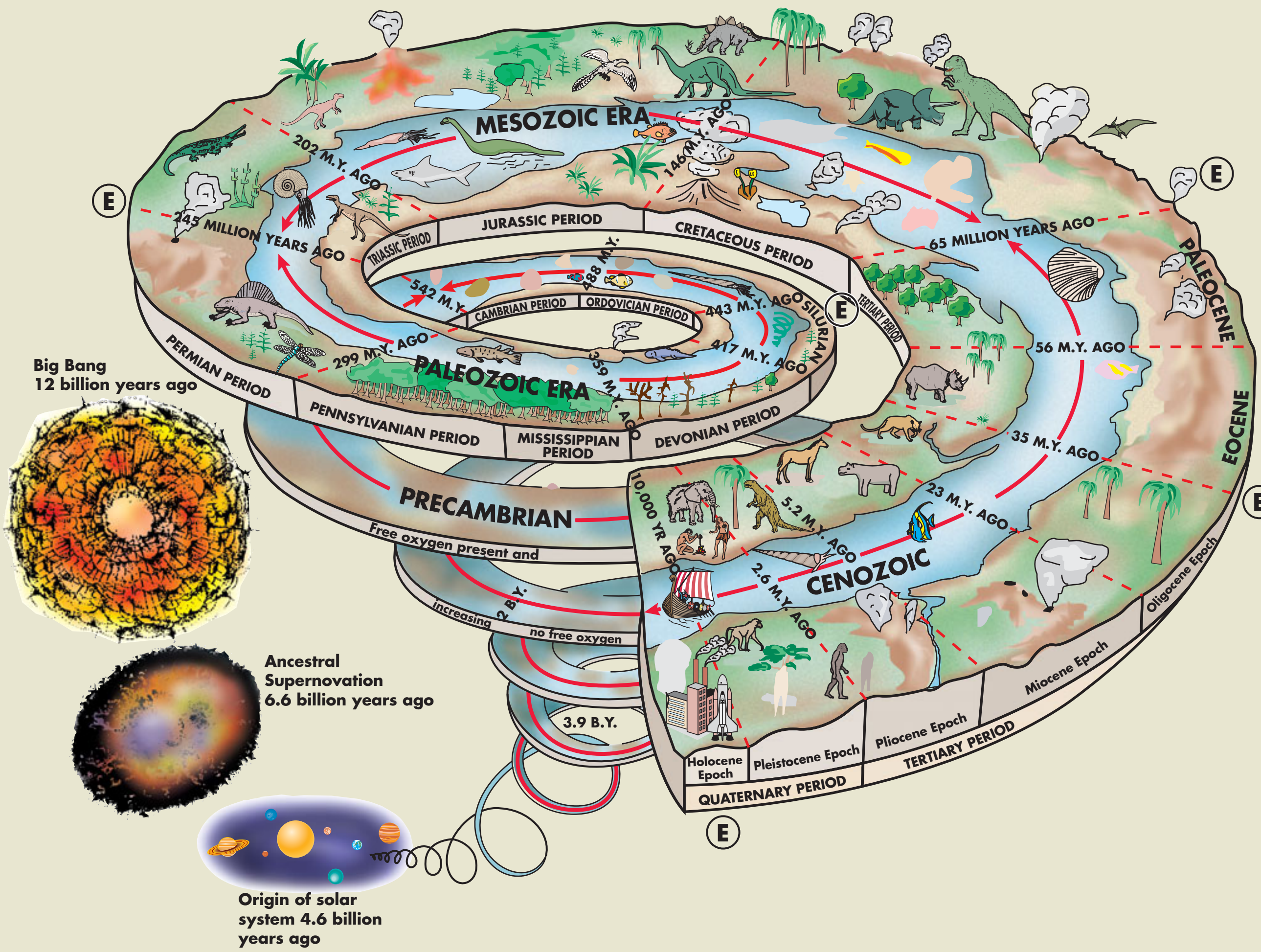


FIGURE 1.A Earth history Idealized diagram of the history of the universe and Earth, with emphasis on the biological evolution of Earth from simple life-forms of the Precambrian to humans today. Precambrian = 4.6 billion years ago to 545 million years ago. Red arrows are boundaries for eras (Table 1.1).(E) is time of mass extinction event. *(Modified after U.S. Geological Survey; and Cloud, P. 1978.* Cosmos, Earth, and man. *New Haven, CT: Yale University Press)*

are based on both the study of what was living at the particular time and on important global geologic events in Earth's history. Relative ages of rocks are based on the assemblage of fossils—that is, evidence for past life, such as shells, bones, teeth, leaves, seeds—that are found in rocks or sediments. A general principle of geology, known as the **law of faunal assemblages**, states that rocks with similar fossils are most likely of a similar geologic age. For example, if we find bones of dinosaurs in a rock, we know the rocks are Mesozoic in age. Fossils provide relative ages of rocks; numerical, or absolute, dates depend upon a variety of sophisticated, chemical age-dating techniques. These age-dating techniques allow geologists to often pinpoint the geologic age of rocks containing fossils to within a few million years or better.

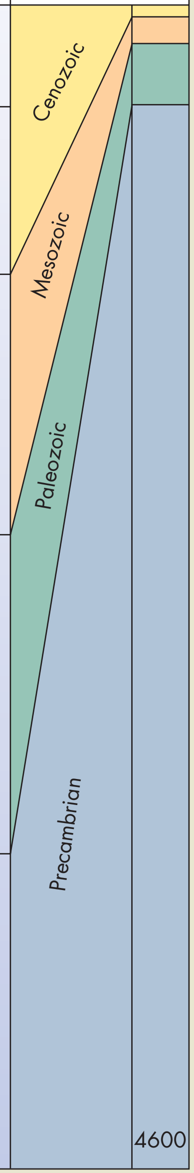
Evolution as a Process. The evolutionary process as deduced from the fossil record has not been a smooth continuous one but, instead, has been punctuated by explosions of new species at some times and extinction of many species at other times. Five mass extinction events are shown in Figure 1.A.

Evolution and extinction of species are natural processes, but, for those times when many species became extinct at approximately the same time, we use the term *mass extinction*. For example, the dinosaurs became extinct approximately 65 million years ago. Some geologists believe this mass extinction resulted

TABLE 1.2 Geologic Time with Important Events

Era	Period	Epoch	Million Years before Present	Events: Life	Events: Earth	Million Years before Present
Cenozoic	Quaternary	Holocene	0.01	• Extinction event • Modern humans	Ice Age Formation of Transverse Ranges, CA	
		Pleistocene	2.6	• Early humans		2.6
	Tertiary	Pliocene	5.2		Formation of Andes Mountains	
		Miocene	23	• Grasses	Collision of India with Asia forming Himalayan Mountains and Tibetan Plateau	
		Oligocene	34	• Whales		
		Eocene	56	• Extinction event		
		Paleocene	65	• Mammals expand	Rocky Mountains form	65
Mesozoic	Cretaceous		146	• Dinosaur extinction[1], extinction event • Flowering plants	Emplacement of Sierra Nevada Granites (Yosemite National Park)	
	Jurassic		202	• Birds	• Supercontinent Pangaea begins to break up	
	Triassic		251	• Mammals • Dinosaurs		251
Paleozoic	Permian		299	• Extinction event • Reptiles	• Ice Age	
	Carboniferous		359	• Trees (coal swamps)		
	Devonian		416	• Extinction event	Appalachian Mountains form	
	Silurian		444	• Land plants		
	Ordovician		488	• Extinction event • Fish		
	Cambrian		542	• Explosion of organisms with shells		542
Precambrian			2500	• Multicelled organisms • Free oxygen in atmosphere and ozone layer in stratosphere	• Ice Age • Ice Age	
			3500	• Primitive life (first fossils)		
			4000		• Oldest rocks	
			4600		• Age of Earth	4600

True Scale (Million Years before Present)



[1]Some scientists believe that not all dinosaurs became extinct but that some dinosaurs evolved to birds. (Geological Society of America, 2009).

from climatic and environmental changes that naturally occurred on Earth; others believe the planet was struck by a "death star," an asteroid of about 10 km (6 mi) in diameter, that crashed into what is today the Yucatan Peninsula in Mexico. It is believed that another such impact would produce firestorms and huge dust clouds that would circle Earth in the atmosphere for a prolonged period of time, blocking out sunlight, greatly reducing or stopping photosynthesis, and eventually leading to mass extinction of both the species that eat plants and the predators that feed on the plant eaters.[7]

It is speculated that asteroids of the size that may have caused the dinosaurs to become extinct are not unique, and such catastrophic impacts have occurred at other times during Earth history. Such an event is the ultimate geologic hazard, the effects of which might result in another mass extinction, perhaps including humans! (See Chapter 11.) Fortunately, the probability of such an occurrence is very small during the next few thousand years. In addition, we are developing the technology to identify and possibly deflect asteroids before they strike Earth. The history of our solar system and Earth, briefly outlined here, is an incredible story of planetary and biological evolution. What will the future bring? We do not know, of course, but, certainly, the future will be punctuated by a change, and, as evolutionary processes continue, we too will evolve, perhaps to a new species. Through the processes of pollution, agriculture, urbanization, industrialization, and the land clearing of tropical forests, humans appear to be causing an acceleration of the rate of extinction of plant and animal species. These human activities are significantly reducing Earth's biodiversity—the number and variability of species over time and space (area)—and are thought to be a major environmental problem because many living things, including humans, on Earth depend on the environment with its diversity of lifeforms for their existence.

2. Natural hazards, such as floods, landslides, earthquakes, and volcanic activity, in order to minimize loss of life and property
3. Land for site selection, land-use planning, and environmental impact analysis
4. Hydrologic processes of groundwater and surface water to evaluate water resources and water pollution problems
5. Geologic processes, such as deposition of sediment on the ocean floor, the formation of mountains, and the movement of water on and below the surface of Earth, to evaluate local, regional, and global change

Considering the breadth of its applications, we can further define environmental geology as the branch of Earth science that studies the entire spectrum of human interactions with the physical environment. In this context, environmental geology is a branch of *environmental science*, the science of linkages between physical, biological, and social processes in the study of the environment.

1.2 Fundamental Concepts of Environmental Geology

Before we begin to explore the many facets of environmental geology presented in this textbook, some basic concepts need to be introduced. These five fundamental concepts serve as a conceptual framework upon which the rest of the textbook will build. As you read through *Introduction to Environmental Geology*, you will notice that these concepts are revisited throughout the text:

1. Human population growth
2. Sustainability
3. Earth as a system
4. Hazardous Earth processes
5. Scientific knowledge and values

The five concepts presented here do not constitute a list of all concepts that are important to environmental geologists, and they are not meant to be memorized. However, having a general understanding of each concept will help you comprehend and evaluate the material presented in the rest of the text.

Concept One: Human Population Growth

The number-one environmental problem is the increase in human population.

The number-one environmental problem is the ever-growing human population. For most of human history, our numbers were small, as was our impact on

Earth. With the advent of agriculture, sanitation, modern medicine, and, especially, inexpensive energy sources, such as oil, we have proliferated to the point where our numbers are a problem. The total environmental impact from people is estimated by the impact per person multiplied by the total number of people. Therefore, as population increases, the total impact must also increase. As population increases, more resources are needed and, given our present technology, greater environmental disruption results. When local population density increases as a result of political upheaval and wars, famine may result (Figure 1.4).

FIGURE 1.4 Famine Korem Camp, Ethiopia, in 1984. Hungry people are forced to flee their homes as a result of political and military activity and gather in camps such as these. Surrounding lands may be devastated by overgrazing from stock animals, gathering of firewood, and just too many people in a confined area. The result may be famine. *(David Burnett/Contact Press Images, Inc.)*

Exponential Growth

What Is the Population Bomb? Overpopulation has been a problem in some areas of the world for at least several hundred years, but it is now apparent that it is a global problem. From 1830 to 1930, the world's population doubled from 1 to 2 billion people. By 1970 it had nearly doubled again, and by the year 2010 there were nearly 7 billion people on Earth. The problem is sometimes called the *population bomb* because the exponential growth of the human population results in an explosive increase in the number of people (Figure 1.5a). **Exponential growth** for increase in humans means that the number of people added to the population each year is not constant; rather, a constant percentage of the current population is added each year. As an analogy, consider a high-yield savings account that pays interest of 7 percent per year. If you start with $100, at the end of the first year you have $107, and you earned $7 in interest. At the end of the second year, 7 percent of $107 is $7.49, and your balance is $107 plus $7.49, or $114.49. Interest in the third year is 7 percent of 114.49, or $8.01, and your account has $122.51. In 30 years you will have saved about $800.00. Read on to find out how I know this.

There are two important aspects of exponential growth:

- The **growth rate**, measured as a percentage
- The **doubling time**, or the time it takes for whatever is growing to double

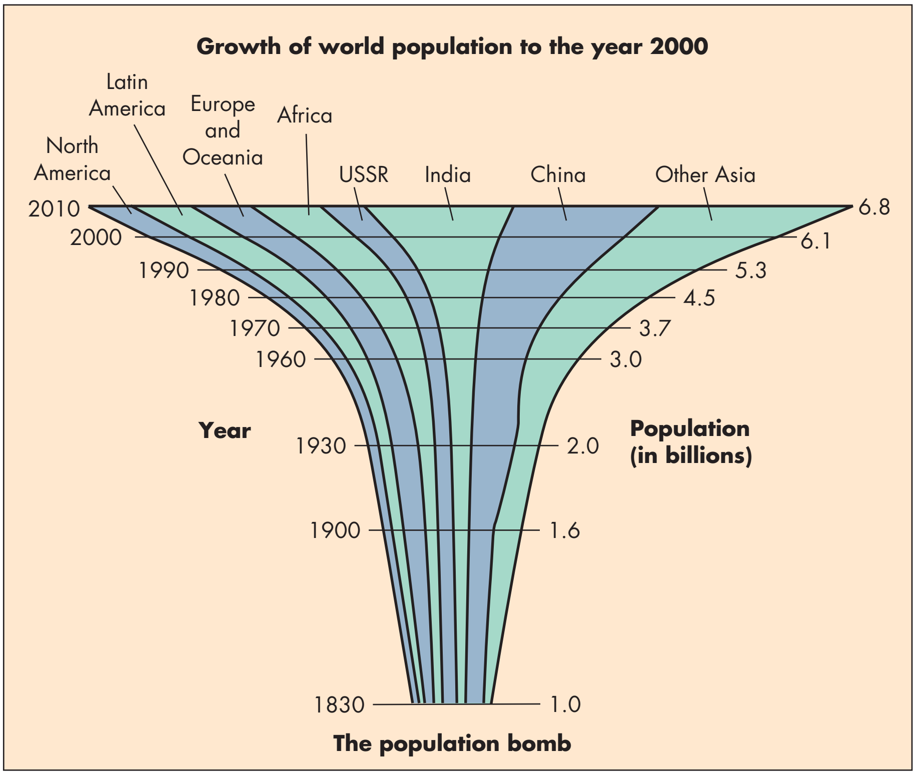
Figure 1.4 illustrates two examples of exponential growth. In each case, the object being considered (student pay or world population) grows quite slowly at first, begins to increase more rapidly, and then continues at a very rapid rate. Even very modest rates of growth eventually produce very large increases in whatever is growing.

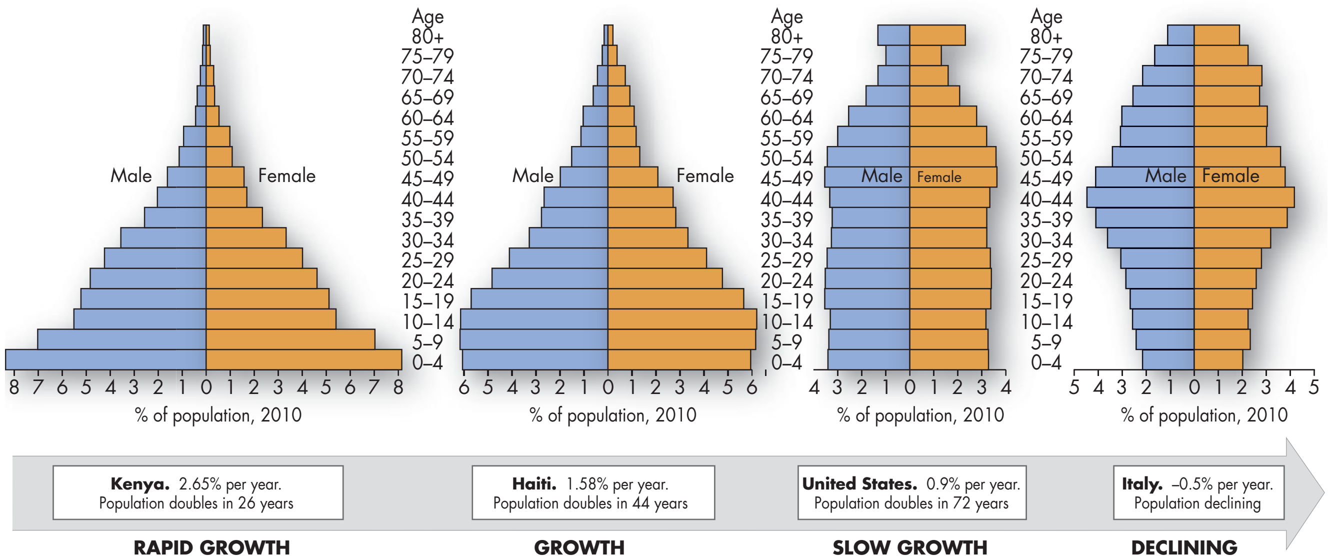
How Fast Does Population Double? A general rule is that doubling time (D) is roughly equal to 70 divided by the growth rate (G):

$$D = 70/G$$

Using this approximation, we find that a population with a 2 percent annual growth rate would double in about 35 years. If it were growing at 1 percent per year, it would double in about 70 years. Figure 1.5b compares four countries (Kenya, Haiti, the United States, and Italy) in terms of age structure (percentage of population at specified age ranges), population growth rate as a percentage per year, and the doubling time. Age structure is important because it is related to socioeconomic issues. Countries with a high percentage of young people under age 15, such as Kenya and Haiti, will have to invest more in education and youth programs. Countries with a young population may also have difficulty with employment.

FIGURE 1.5 The population bomb (a) The population in 2009 was 6.8 billion and growing. *(Modified after U.S. Department of State).* (b) Age structure for selected countries, with growth rates and doubling times. Countries with declining populations include Germany, Italy, Japan, and Russia. The fastest growth is in Liberia, at 4.5 percent per year (doubling time 16 years). *(Data from CIA World Facts 2010. www.cia.gov)*





Lack of employment can result in social unrest. Countries with an older population, such as Italy, will have to provide more for health programs for the elderly. Providing retirement benefits may be difficult as the percentage of older people grows compared to people working to support social services.

Returning to our discussion of exponential growth, many systems in nature display exponential growth some of the time, so it is important that we be able to recognize such growth because it can eventually yield incredibly large numbers. As an extreme example of exponential growth (**Figure 1.6a**), consider the student who, after taking a job for 1 month, requests from the employer a payment of 1 cent for the first day of work, 2 cents for the second day, 4 cents for the third day, and so on. In other

words, the payment would double each day. What would be the total? It would take the student 8 days to earn a wage of more than $1 per day, and by the eleventh day, earnings would be more than $10 per day. Payment for the sixteenth day of the month would be more than $300, and on the last day of the 31-day month, the student's earnings for that one day would be more than $10 million! This is an extreme case because the constant rate of increase is 100 percent per day, but it shows that exponential growth is a very dynamic process. The human population increases at a much lower rate—1.4 percent per year today—but even this slower exponential growth eventually results in a dramatic increase in numbers (**Figure 1.6b**).

Consider the often-cited analogy of a farmer with a 100-acre (40 ha) pond. The pond is invaded by an exotic water plant (i.e., an invasive species) that floats on the surface, covering the water with a thick mat of vegetation. The farmer observes that the plant doubles its area every 2 weeks. At first the growth appears slow, as the plant grows to covers a small part of the pond. The farmer decides to eliminate the plant when it covers one-fourth of the pond. How much time will he have? He will have only 4 weeks! One-fourth of the pond doubles to one-half in 2 weeks, and in another 2 weeks, the pond would be completely covered by the invasive species.

Exponential growth will be discussed further under Concept Three, when we consider systems and change.

Human Population Through History

What Is Our History of Population Growth?

The story of human population increase is put in historic perspective in **Table 1.3**. When we were hunter-gatherers, our numbers were very small, and growth rates were very low. With agriculture, growth rates in human population increased by several hundred times, due to the stable food supply. During the early industrial period (A.D. 1600 to 1800), growth rates increased again by about 10 times. With the Industrial Revolution, with modern sanitation and medicine, the growth rates increased another 10 times. Human population reached 6 billion in 2000. By 2013 it will be 7 billion, and by 2050 it will be about 9 billion. That is 1 billion new people in only 13 years and 3 billion (almost one-half of today's population) in 50 years. By comparison, total human population had reached only 1 billion in about A.D. 1800, after over 40,000 years of human history! Less developed countries have death rates similar to those of more developed countries, but their birth rates are twice those of developed countries. India will likely have the greatest population of all countries by 2050, with about 18 percent of the total world population,

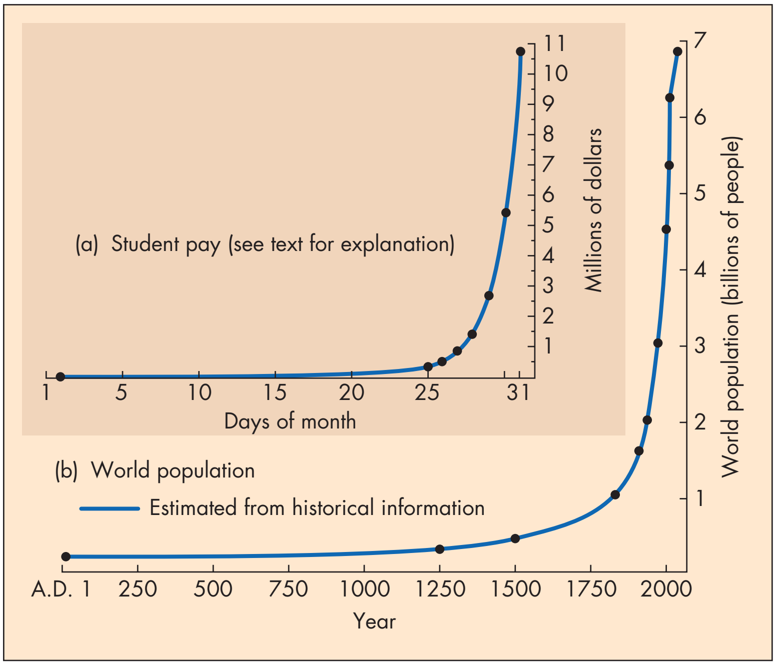


FIGURE 1.6 Exponential growth (a) Example of a student's pay, beginning at 1 cent for the first day of work and doubling daily for 31 days. (b) World population. Notice that both curves have the characteristic *J* shape, with a slow initial increase followed by a rapid increase. The actual shape of the curve depends on the scale at which the data are plotted. It often looks like the tip of a skateboard. *(Population data from U.S. Department of State)*

TABLE 1.3 How We Became 6 Billion

40,000–9,000 B.C.: Hunters and Gatherers
Population density about 1 person per 100 km^2 of habitable areas;[1] total population probably less than a few million; average annual growth rate less than 0.0001% (doubling time about 700,000 years)
9,000 B.C.–A.D. 1600: Preindustrial Agricultural
Population density about 1 person per 3 km^2 of habitable areas (about 300 times that of the hunter and gatherer period); total population about 500 million; average annual growth rate about 0.03% (doubling time about 2,300 years)
A.D. 1600–1800: Early Industrial
Population density about 7 persons per 1 km^2 of habitable areas; total population by 1800 about 1 billion; annual growth rate about 0.1% (doubling time about 700 years)
A.D. 1800–2000: Modern
Population density about 40 persons per 1 km^2; total population in 2000 about 6.1 billion; annual growth rate at 2000 about 1.4% (doubling time about 50 years)

[1]Habitable area is assumed to be about 150 million square kilometers (58 million square miles). Modified after Botkin, D. B., and Keller, E. A. 2000. *Environmental science*, 3rd ed. New York: John Wiley and Sons.

followed by China, with 15 percent. Together, these two countries will have about one-third of the total world population by 2050.[8]

Population Growth and the Future

How Many People Can Earth Comfortably Support? Because Earth's population is increasing exponentially, many scientists are concerned that in the twenty-first century it will be impossible to supply resources and a high-quality environment for the billions of people who may be added to the world population. Three billion more people by 2050, with almost all of the growth in the developing countries, is cause for concern. Increasing population at local, regional, and global levels compounds nearly all environmental geology problems, including pollution of ground and surface waters; production and management of hazardous waste; and exposure of people and human structures to natural processes (hazards), such as floods, landslides, volcanic eruptions, and earthquakes.

There is no easy answer to the population problem. In the future, we may be able to mass-produce enough food from a nearly landless agriculture or use artificial growing situations to support our ever-growing numbers. However, the ability to feed people does not solve the problems of limited space available to people and maintenance or improvement of their quality of life. Some studies suggest that the present population is already above a comfortable **carrying capacity** for the planet. Carrying capacity is the maximum number of people Earth can hold without causing environmental degradation that reduces the ability of the planet to support the population. The role of education is paramount in the population problem. As people (particularly women) become more educated, the population growth rate tends to decrease. As the rate of literacy increases, population growth is reduced. Given the variety of cultures, values, and norms in the world today, it appears that our greatest hope for population control is, in fact, education.[9]

Earth Is Our Only Suitable Habitat. Earth is now and for the foreseeable future the only suitable habitat we have, and its resources are limited. Some resources, such as water, are renewable, but many, such as fuels and minerals, are not. Other planets in our solar system, such as Mars, cannot currently be considered a solution to our resource and population problems. We may eventually have a colony of people on Mars, but it would be a harsh environment, with people living in bubbles.

When resource and other environmental data are combined with population growth data, the conclusion is clear: It is impossible, in the long run, to support exponential population growth with a finite resource base. Therefore, one of the primary goals of environmental work is to ensure that we can defuse the population bomb. Some scientists believe that

population growth will take care of itself through disease and other catastrophes, such as famine. Other scientists are optimistic that we will find better ways to control the population of the world within the limits of our available resources, space, and other environmental needs.

Good News on Human Population Growth. It is not all bad news regarding human population growth; for the first time since the mid-1900s, the rate of increase in human population is decreasing. Figure 1.7 shows that the number of people added to the total population of Earth peaked in the late 1980s and has generally decreased since then. This is a milestone in human population growth, and it is encouraging.[10] From an optimistic point of view, it is possible that our global population of 6 billion persons in 2000 may not double again. Although population growth is difficult to estimate because of variables such as agriculture, sanitation, medicine, culture, and education, it is estimated that by the year 2050 about 40 million new people will be added (today, about 74 million are added each year), and the human population will be about 9 billion. Population reduction is most likely related to the education of women, the decision to marry later in life, and the availability of modern birth control methods. Until the growth rate is zero, however, population will continue to grow. About 20 countries, mostly in Western Europe but including China, have achieved a total fertility rate (number of children per woman) less than 2.1, which is the level necessary for replacement.

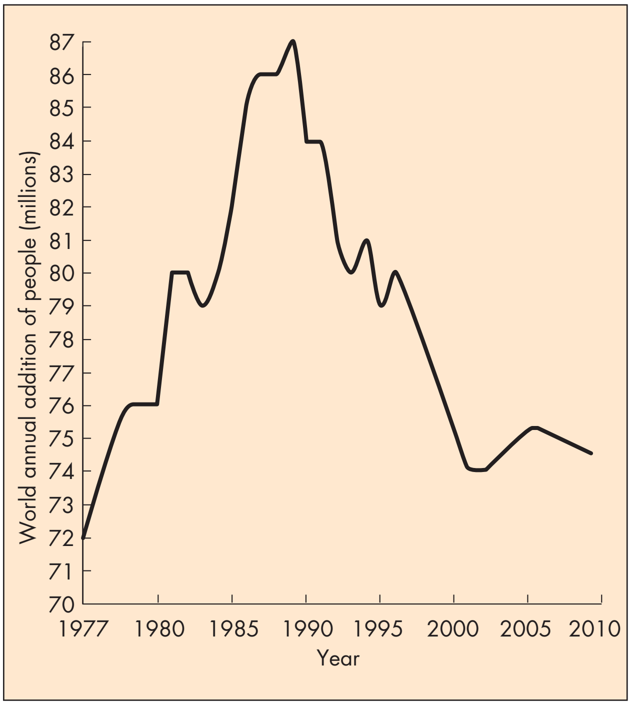


FIGURE 1.7 Good news on population growth World annual increase in population peaked in the late 1980s. Today it is at a level comparable to the late 1970s. This increase is like adding two Californias each year. *(Data from the U.S. Bureau of the Census and Worldwatch Institute)*

Concept Two: Sustainability

Sustainability is the environmental objective.

What is sustainability? **Sustainability** is something that we are struggling to define. One definition is that sustainability is development which ensures that future generations will have equal access to the resources that our planet offers. Sustainability also refers to types of development that are economically viable, do not harm the environment, and are socially just.[9] Sustainability is a long-term concept, something that happens over decades or even over hundreds of years. It is important to acknowledge that sustainability with respect to use of resources is possible for renewable resources such as air and water. Sustainable development with respect to nonrenewable resources such as fossil fuels and minerals is possible by, first, extending their availability through conservation and recycling; and second, rather than focusing on when a particular nonrenewable resource is depleted, focusing on how that mineral is used and developing substitutes for those uses.

There is little doubt that we are using living environmental resources, such as forests, fish, and wildlife, faster than they can be naturally replenished. We have extracted minerals, oil, and groundwater without concern for their limits or for the need to recycle them. As a result, there are shortages of some resources. We must learn how to sustain our environmental resources so that they continue to provide benefits for people and other living things on the planet.

We stated in Concept One, with respect to humans and resources, that Earth is the only place to live that is now accessible to us, and our resources are limited. To meet future resource demands and to sustain our resources, we will need large-scale recycling of many materials. Most materials can theoretically

be recycled. The challenge is to find ways to do it that do not harm the environment, that increase the quality of life, and that are economically viable. A large part of our solid and liquid waste disposal problems could be alleviated if these wastes were reused or recycled. In other words, many wastes that are now considered pollutants can be turned into resources. Land is also an important resource for people, plants, and animals, as well as for manufacturing, mining, and energy production; transportation; deposition of waste products; and aesthetics. Due in part to human population increases that demand more land for urban and agricultural purposes, human-induced change to Earth is increasing at a rapid rate. A recent study of human activity and the ability to move soil and rock concluded that human activity (agriculture, mining, urbanization, and so on) moves as much or more soil and rock on an annual basis than any other Earth process (**Figure 1.8**), including mountain building and river transport of sediment. These activities and their associated visual changes to Earth (e.g., leveling hills) suggest that human activity is the most significant process shaping the surface of Earth.[11] We'll discuss land use planning in Chapter 19.

FIGURE 1.8 Mining A giant excavating machine in this mine can move Earth materials at a rate that could bury one of the Egyptian Pyramids in a short time. *(GMVozd/iStockphoto)*

Are We in an Environmental Crisis? Demands made on diminishing resources by a growing human population and the ever-increasing production of human waste have produced what is popularly referred to as the **environmental crisis**. This crisis in the United States and throughout the rest of the world is a result of overpopulation, urbanization, and industrialization, combined with too little ethical regard for our land and inadequate institutions to cope with environmental stress.[12] The rapid use of resources continues to cause environmental problems on a global scale, including the following:

- Deforestation and accompanying soil erosion and water and air pollution occur on many continents (**Figure 1.9a**).
- Mining of resources, such as metals, coal, and petroleum, wherever they occur produces a variety of environmental problems (**Figure 1.9b**).
- Development of both groundwater and surface-water resources results in loss of and damage to many environments on a global scale (see Case History: The Aral Sea: The Death of a Sea).

On a positive note, we have learned a great deal from the environmental crisis, particularly concerning the relationship between environmental degradation and resource utilization. Innovative plans for sustainable development of resources, including water and energy, are being developed to lessen a wide variety of environmental problems associated with using resources.

Do We Need to Save Earth or Ourselves? The environmental slogan of the 1990s was "save our planet." Is Earth's very survival really in danger? In the long view of planetary evolution, it seems highly likely that Earth will outlive the human race. Our Sun is likely to last another several billion years at least, and even if all humans became extinct in the next few years, life would still flourish on our planet. The environmental degradation we have imposed on the landscape, atmosphere, and waters might last for a few hundred or thousand years, but they would eventually be cleansed by natural processes. Therefore, our major concern is the quality of the human environ-

FIGURE 1.9A Logging Clear-cut timber harvesting exposes soils, compacting them and generally contributing to an increase in soil erosion and other environmental problems. *(Edward A. Keller)*

FIGURE 1.9B Mining Large open pit mines such as this one east of Silver City, New Mexico, are necessary if we are to obtain resources. However, they cause disturbance to the surface of the land, and reclamation may be difficult or nearly impossible in some instances. *(Michael Collier)*

ment, which depends on sustaining our larger support systems, including air, water, soil, and other life.

Concept Three: Earth as a System

Understanding Earth's systems and their changes is critical to solving environmental problems.

A **system** is any defined part of the universe that we select for study. Examples of systems are a planet, a volcano, an ocean basin, and a river (**Figure 1.10**, page 21). Most systems contain several component parts that mutually adjust to function as a whole, with changes in one component bringing about changes in other components. For example, the components of our global system are water, land, atmosphere, and life. These components mutually adjust, helping to keep the entire Earth system operating.

Input–Output Analysis

Input–output analysis is an important method for analyzing change in open systems. **Figure 1.11** (page 21) identifies three types of change in a pool or stock of materials; in each case, the net change depends on the relative rates of the input and output. Where the input into the system is equal to the output (Figure 1.11a), a rough steady state is established, and no net change occurs. The example shown is a university in which students enter as freshmen and graduate 4 years later, at a constant rate. Thus, the pool of university students remains a constant size. At the global scale, our planet is a roughly steady-state system with respect to energy: Incoming solar radiation is roughly balanced by outgoing radiation from Earth. In the second type of change, the input into the system is less than the output (Figure 1.11b). Examples include the use of resources, such as fossil fuels or groundwater and

Case History

The Aral Sea: The Death of a Sea

The Aral Sea, located between Kazakhstan and Uzbekistan, formerly part of the Union of Soviet Socialist Republics, was a prosperous tourist vacation spot in 1960. Water diversion for agriculture nearly eliminated the Aral Sea in a period of only 30 years. It is now a dying sea surrounded by thousands of square kilometers of salt flats, and the change is permanently damaging the economic base of the region.

In 1960 the area of the Aral Sea was about 67,000 km^2 (around 26,200 mi^2). Diversion of the two main rivers that fed the sea has resulted in a drop in surface elevation of more than 20 m (66 ft) and loss of about 28,000 km^2 (10,800 mi^2) of surface area (**Figure 1.B**). Towns that were once fishing centers on the shore are today about 30 km (19 mi) inland. Loss of the sea's moderating effect on weather is changing the regional climate; the winters are now colder and the summers warmer. Windstorms pick up salty dust and spread it over a vast area, damaging the land and polluting the air.

The lesson to be learned from the Aral Sea is how quickly environmental damage can bring about regional change. Environmentalists, including geologists, worry that what people have done to the Aral region is symptomatic of what we are doing on many fronts on a global scale.[13] Today an ambitious restoration project is underway to save the northern, smaller part of the lake. A low 13 km-long dam (dike) has been constructed across the lake just south of where the Syr Darya flows into the lake (see Figure 1.B). With water conservation of the river water, more water is flowing in the lake, and the dam keeps the water in the northern part of the lake bed. Water levels there are rising, and some fishing has returned. This is a promising sign, but much more needs to be done.

(a)

(b)

FIGURE 1.B Dying sea (a) The Aral Sea is a dying sea, surrounded by thousands of square kilometers of salt flats. *(Courtesy of Philip P. Micklin)* (b) Water diversion for agriculture has nearly eliminated the sea. The two ships shown here are stranded high and dry along the shore line, which contains extensive salt flats formed as the Aral Sea has evaporated. *(David Turnley/Corbis)*

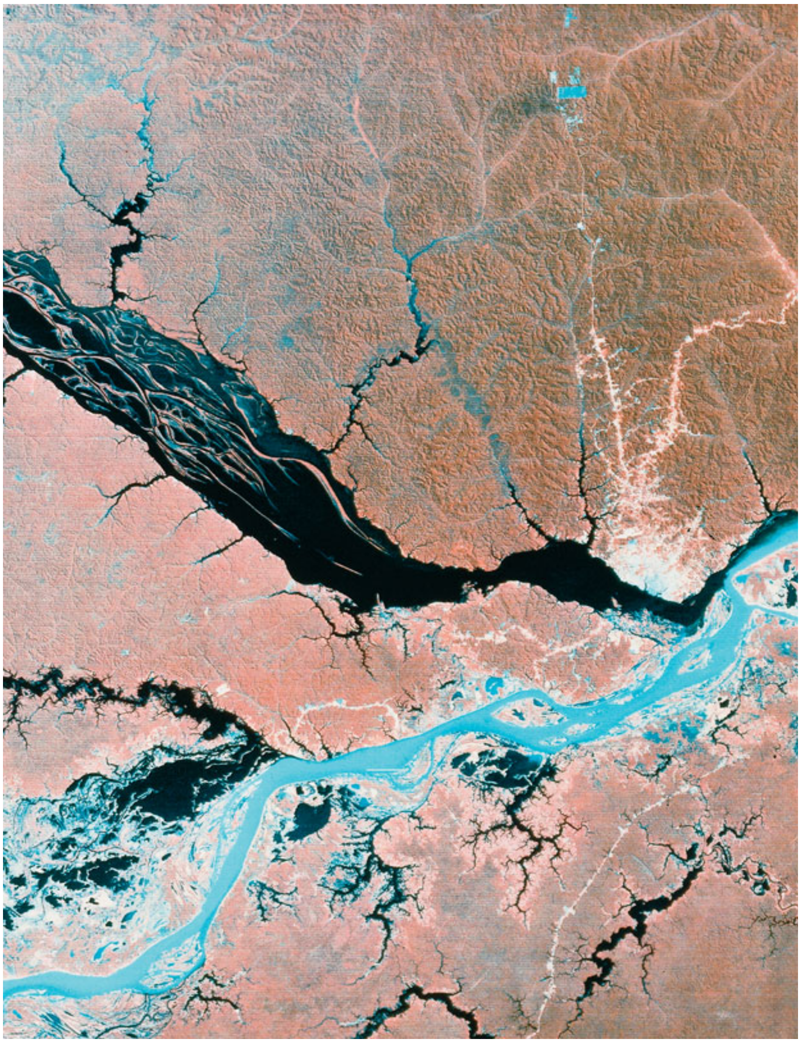


FIGURE 1.10 River as a system Image of part of the Amazon River system (blue) and its confluence with the Rio Negro (black). The blue water of the Amazon is heavily laden with sediment, whereas the water of the Rio Negro is nearly clear. Note that as the two large rivers join, the waters do not mix initially but remain separate for some distance past the confluence. The Rio Negro is in flood stage. The red is the Amazon rain forest, and the white lines are areas of human-caused disturbances such as roads. *(Earth Satellite Corporation/Science Photo Library/Photo Researchers, Inc.)*

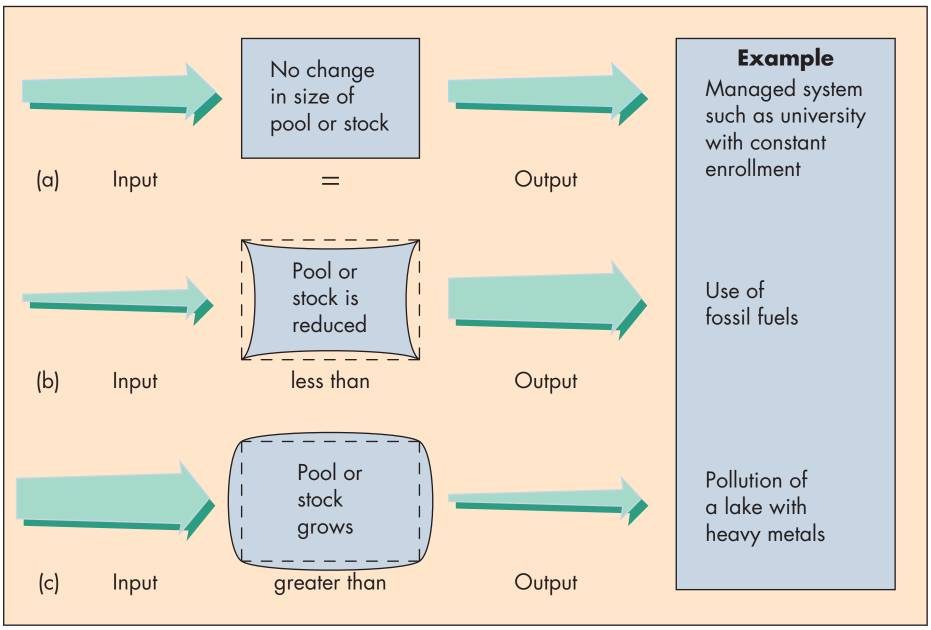


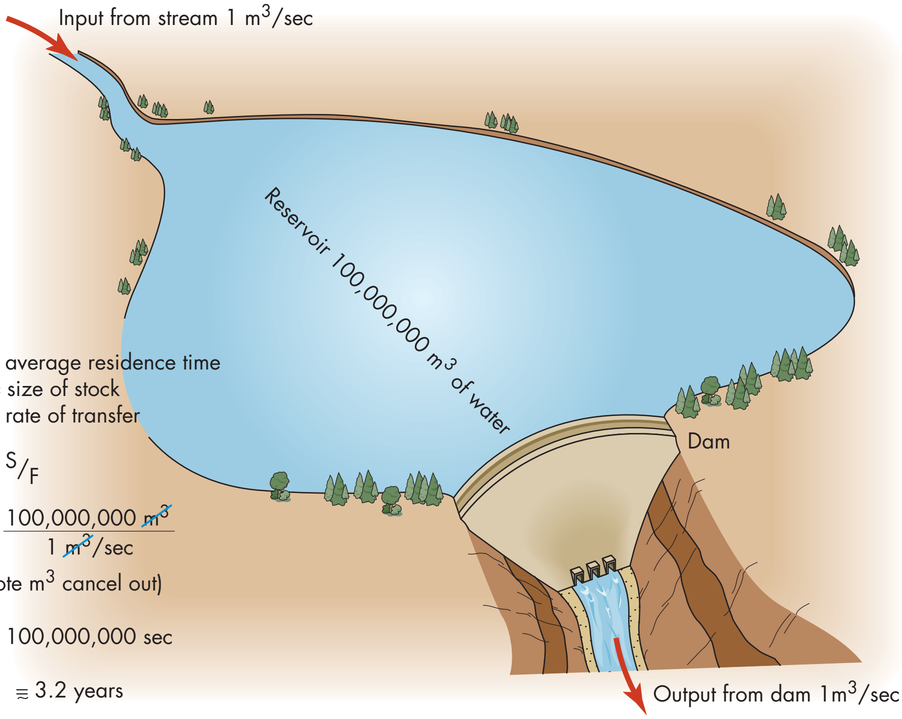
FIGURE 1.11 Change in systems Major ways in which a pool or stock of some material may change. *(Modified after Ehrlich, P. R., Ehrlich, A. H., and Holdren, J. P. 1977.* Ecoscience: Population, Resources, Environment, *3rd ed. San Francisco: W. H. Freeman)*

the harvest of certain plants or animals. If the input is much less than the output, the fuel or water source may be completely used up or the plants or animals may become extinct. In a system in which input exceeds output (Figure 1.11c), the stock of whatever is being measured will increase. Examples include the buildup of heavy metals in lakes from industrial pollution or the pollution of soil and water.

How Can We Evaluate Change? By evaluating rates of change or the input and output of a system, we can derive an **average residence time** for a particular material, such as a resource. The average residence time is a measure of the time it takes for the total stock or supply of the material to be cycled through a system. To compute the average residence time (T; assuming constant size of the system and constant rate of transfer), we take the total size of the stock (S) and divide it by the average rate of transfer (F) through the system:

$$T = S/F$$

For example, if a reservoir holds 100 million cubic meters of water, and both the average input from streams entering the reservoir and the average output over the spillway are 1 cubic meter per second, then the average residence time for a cubic meter of water in the reservoir is 100 million seconds, or about 3.2 years (**Figure 1.12**). We can also calculate average residence time for systems that vary in size and rates of transfer, but the mathematics is more difficult. It is often possible to compute a residence time for a particular resource and then to apply the information to help understand and solve environmental problems. For example, the average residence time of water in rivers is about 2 weeks, compared with thousands of years for some groundwater. Thus, strategies to treat a one-time pollution event of oil spilled in a river will be much different from those for removing oil floating on groundwater that resulted from a rupture of an underground pipeline. The oil in the river is a relatively accessible, straightforward, short-term problem, whereas polluted groundwater is a more difficult problem because it moves slowly and has a long average residence time. Because it may take from several to hundreds of



T = average residence time
S = size of stock
F = rate of transfer

$$T = {}^{S}/_{F}$$

$$T = \frac{100{,}000{,}000\ \cancel{m^3}}{1\ \cancel{m^3}/\text{sec}}$$

(Note m^3 cancel out)

$$T = 100{,}000{,}000 \text{ sec}$$

$$\cong 3.2 \text{ years}$$

FIGURE 1.12 Average residence time Calculation of the average residence time for a cubic meter of water in a reservoir where input = output = 1 m^3 per second and the size of the reservoir is constant at 100,000,000 m^3 of water.

years for pollution of groundwater to be naturally removed, groundwater pollution is difficult to treat.

Predicting Changes in the Earth System

The idea that "the present is the key to the past," called **uniformitarianism**, was popularized by James Hutton, referred to by some scholars as the father of geology, in 1785. It is heralded today as a fundamental concept of Earth sciences. As the name suggests, uniformitarianism holds that processes we observe today also operated in the past (e.g., flow of water in rivers, formation and movement of glaciers, landslides, waves on beaches, uplift of the land from earthquakes). Uniformitarianism does not demand or even suggest that the magnitude (i.e., amount of energy expended) and frequency (i.e., how often a particular process occurs) of natural processes remain constant with time. We can infer that, for as long as Earth has had an atmosphere, oceans, and continents similar to those of today, the present processes were operating.

Present Human Activity Is Part of the Key to Understanding the Future. In making inferences about geologic events, we must consider the effects of human activity on the Earth system and what effect these changes to the system as a whole may have on natural Earth processes. For example, rivers flood regardless of human activities, but human activities, such as paving the ground in cities, increase runoff and the magnitude and frequency of flooding. That is, after the paving, floods of a particular size are more frequent, and a particular rainstorm can produce a larger flood than before the paving. Therefore, to predict the long-range effects of flooding, we must be able to determine how future human activities will change the size and frequency of floods. In this case, *the present is the key to the future*. For example, when environmental geologists examine recent landslide deposits (**Figure 1.13**) in an area designated to become a housing development, they must use uniformitarianism to infer where there will be future landslides as well as to predict what effects urbanization will have on the magnitude and frequency of future landslides. We will now consider linkages between processes.

Environmental Unity

The principle of **environmental unity**, which states that one action causes others in a chain of actions, is

FIGURE 1.13 Urban development The presence of a landslide on this slope suggests that the slope is not stable and further movement may occur in the future. This is a red flag for future development in the area. *(Edward A. Keller)*

A Closer Look

The Gaia Hypothesis

Is Earth Analogous to an Organism? In 1785, at a meeting of the prestigious Royal Society of Edinburgh, James Hutton, the father of geology, said he believed that planet Earth is a superorganism (**Figure 1.C**). He compared the circulation of Earth's water, with its contained sediments and nutrients, to the circulation of blood in an animal. In Hutton's metaphor, the oceans are the heart of Earth's global system, and the forests are the lungs.[14] Two hundred years later, British scientist and professor James Lovelock introduced the **Gaia hypothesis**, reviving the idea of a living Earth. The hypothesis is named for Gaia, the Greek goddess Mother Earth.

The Gaia hypothesis is best stated as a series of hypotheses:

FIGURE 1.C Home Image of Earth centering on the North Atlantic Ocean, North America, and the polar ice sheets. Given this perspective of our planet, it is not difficult to conceive it as a single large system. *(Terra Globe/NASA)*

- *Life significantly affects the planetary environment.* Very few scientists would disagree with this concept.
- *Life affects the environment for the betterment of life.* This hypothesis is supported by some studies showing that life on Earth plays an important role in regulating planetary climate, so that it is neither too hot nor too cold for life to survive. For example, it is believed that single-cell plants floating near the surface of the ocean partially control the carbon dioxide content of the atmosphere and thereby global climate.[14]
- *Life deliberately or consciously controls the global environment.* Very few scientists accept this third hypothesis. Interactions and the linking of processes that operate in the atmosphere, on the surface of Earth, and in the oceans are probably sufficient to explain most of the mechanisms by which life affects the environment. In contrast, humans are beginning to make decisions concerning the global environment, so the idea that humans can consciously influence the future of Earth is not an extreme view. Some people have interpreted this idea as support for the broader Gaia hypothesis.

Gaia Thinking Fosters Interdisciplinary Thinking. The real value of the Gaia hypothesis is that it has stimulated a lot of interdisciplinary research to understand how our planet works. As interpreted by most scientists, the hypothesis does not suggest foresight or planning on the part of life but, rather, that natural processes are operating.

an important principle in the prediction of changes in the Earth system. For example, if we constructed a dam on a river, a number of changes would occur. Sediment that moved down the river to the ocean before construction of the dam would be trapped in the reservoir. Consequently, beaches would be deprived of the sediment from the river, and the result of that deprivation might be increased coastal erosion. Having less sediment on the beach may also affect coastal animals that use the sand, such as sand crabs and clams. Thus, building the dam would set off a chain or series of effects that would change the coastal environment and what lived there. The dam would also change the hydrology of the river and would block fish from migrating upstream. We will now consider global linkages.

Earth Systems Science

Earth systems science is the study of the entire planet as a system in terms of its components (see A Closer Look: The Gaia Hypothesis). It asks how

component systems (i.e., subsystems of the Earth system)—such as the atmosphere (air), hydrosphere (water), biosphere (life), and lithosphere (rocks)—are linked and have formed, evolved, and been maintained; how these components function; and how they will continue to evolve over periods ranging from a decade to a century and longer.[15] Because these systems are linked, it is also important to understand and be able to predict the impacts of a change in one component on the others. The challenge is to learn to predict changes that are likely to be important to society and then to develop management strategies to minimize adverse environmental impacts. For example, the study of atmospheric chemistry suggests that our atmosphere has changed over millennia. Trace gases such as carbon dioxide have increased by about 100 percent since 1850. Chlorofluorocarbons (CFCs), used as refrigerants and aerosol-can propellants, released at the surface have migrated to the stratosphere, where they react with energy from the Sun, causing destruction of the ozone layer that protects Earth from harmful ultraviolet radiation. The important topics of global change and Earth systems science will be discussed in Chapter 18, following topics such as Earth materials, natural hazards, and energy resources.

Concept Four: Hazardous Earth Processes

There have always been Earth processes that are hazardous to people. These natural hazards must be recognized and avoided when possible, and their threat to human life and property must be minimized.

We humans, like all other animals, have to contend with natural processes, such as storms, floods, earthquakes, landslides, and volcanic eruptions, that periodically damage property and kill us. During the past 20 years, natural hazards on Earth have killed several million people. The annual loss has been about 150,000 people, with financial damages of about $20 billion.

Natural Hazards That Produce Disasters Are Becoming Superdisasters Called Catastrophes. Early in human history, our struggle with natural Earth processes was mostly a day-to-day experience. Our numbers were neither great nor concentrated, so losses from hazardous Earth processes were not significant. As people learned to produce and maintain a larger and, in most years, more abundant food supply, the population increased and became more concentrated locally. The concentration of population and resources also increased the impact that periodic earthquakes, floods, and other natural disasters had on humans. This trend has continued, so that many people today live in areas likely to be damaged by hazardous Earth processes or susceptible to the adverse impact of such processes in adjacent areas. An emerging principle concerning natural hazards is that, as a result of human activity (e.g., population increase and changing the land through agriculture, logging, mining, urbanization), what were formerly disasters are becoming catastrophes. For example:

- Human population increase has forced more people to live in hazardous areas, such as in floodplains, on steep slopes (where landslides are more likely), and near volcanoes.
- Land-use transformations, including urbanization and deforestation, increase runoff and flood hazard and may weaken slopes, making landslides more likely.
- Burning vast amounts of oil, gas, and coal has increased the concentration of carbon dioxide in the atmosphere, contributing to warming the atmosphere and oceans. As a result, more energy is fed into hurricanes. The number of hurricanes has not increased, but the intensity and size of the storms have increased.

We can recognize many natural processes and predict their effects by considering climatic, biological, and geologic conditions. After Earth scientists have identified potentially hazardous processes, they have the obligation to make the information available to planners and decision makers who can then consider ways of avoiding or minimizing the threat to human life or property. Put concisely, this process consists of assessing the risk of a certain hazard in a given area and basing planning decisions on that risk assessment. Public perception of hazards also plays a role in the determination of risk from a hazard. For example, although they probably understand that the earthquake hazard in southern California is real, the residents who have never experienced an earthquake firsthand may

have less appreciation for the seriousness of the risk of loss of property and life than do persons who have experienced an earthquake.

Concept Five: Scientific Knowledge and Values

The results of scientific inquiry to solve a particular environmental problem often provide a series of potential solutions consistent with the scientific findings. The chosen solution is a reflection of our value system.

What Is Science? To understand our discussion of scientific knowledge and values, we need to first have an appreciation for the conventions of scientific inquiry. Most scientists are motivated by a basic curiosity about how things work. Geologists are excited by the thrill of discovering something previously unknown about how the world works. These discoveries drive them to continue their work. Given that we know little about internal and external processes that form and maintain our world, how do we go about studying it? The creativity and insight that may result from scientific breakthroughs often begin with asking questions pertinent to some problem of interest to the investigators. If little is known about the topic or process being studied, they will first try to conceptually understand what is going on by making careful observations in the field or, perhaps, in a laboratory. On the basis of his or her observations, a scientist may then develop a question or a series of questions about those observations. Next, the investigator will suggest an answer or several possible answers to the question. The possible answer is a **hypothesis** to be tested. The best hypotheses can be tested by designing an experiment that involves data collection, organization, and analysis. After collection and analysis of the data, the scientist interprets the data and draws a conclusion. The conclusion is then compared with the hypothesis, and the hypothesis may be rejected or tentatively accepted. Often, a series of questions or multiple hypotheses are developed and tested. If all hypotheses suggested to answer a particular question are rejected, then a new set of hypotheses must be developed. This method is sometimes referred to as the **scientific method**. The steps of the scientific method are shown in **Figure 1.14**. The first step of the scientific method is the formation of a question—in this case, "Where does beach sand come from?" In order to explore this question, the scientist spends some time at the beach. She notices some small streams that flow into the ocean; she knows that the streams originate in the nearby mountains. She then refines her question to ask specifically, "Does beach sand come from the mountains to the beach by way of streams?" This question is the basis for the scientist's hypothesis: Beach sand originates in the mountains. To test this hypothesis, she collects some sand from the beach and from the streams and some rock samples from the mountains. She then compares their mineral content. She finds that the mineral content of all three is roughly the same. She draws a conclusion that the beach sand does come from the mountains, and, so, accepts her hypothesis. If her hypothesis had proved to be wrong, she would have had to formulate a new hypothesis. In complex geologic problems, multiple hypotheses may be formulated and each one tested. This is the method of multiple working hypotheses. If a hypothesis withstands the testing of a sufficient number of experiments, it may be accepted as a **theory**. A theory is a strong scientific statement that the hypothesis supporting the theory is likely to be true but has not been proved conclusively. New evidence often disproves existing hypotheses or scientific theory; absolute proof of scientific theory is not possible. Thus, much of the work of science is to develop and test hypotheses, striving to reject current hypotheses and to develop better ones.

Laboratory studies and fieldwork are commonly used in partnership to test hypotheses, and geologists often begin their observations in the field or in the laboratory by taking careful notes. For example, a geologist in the field may create a *geologic map*, carefully noting and describing the distribution of different Earth materials. The map can be completed in the laboratory, where the collected material can be analyzed.

An important aspect of science not often discussed in detail is concerned with the roles of knowledge, imagination, and creative critical thinking. If we have prepared our mind to do science by studying mathematics, physics, chemistry, hydrology, and geology, we may be more able to link basic science to a particular problem, such as why and how erosion occurs. It is helpful to be able to imagine the processes occurring that play a role in a

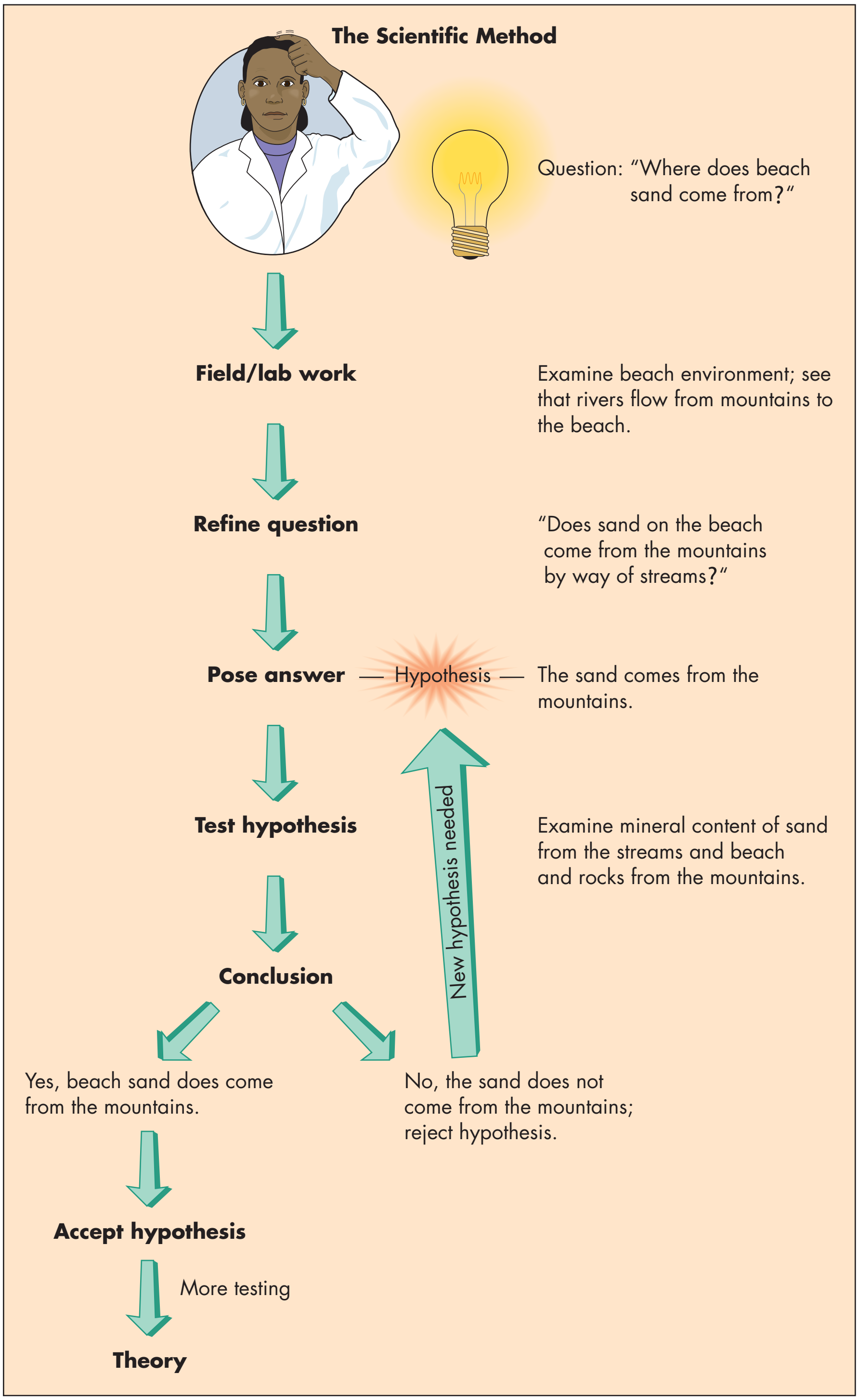


FIGURE 1.14 Science The steps in the scientific method.

particular location (see A Closer Look: Knowledge, Imagination, and Critical Thinking).

The important variable that distinguishes geology from most of the other sciences is the consideration of time (see the geologic time scale in Table 1.2). Geologists' interest in Earth history over time periods that are nearly incomprehensible to most people naturally leads to some interesting questions:

- How fast are mountains uplifted and formed?
- How fast do processes of erosion reduce the average elevation of the land?

A Closer Look

Knowledge, Imagination, and Critical Thinking

Knowledge and Imagination. In science, imagination is the ability to form a mental image or idea of a process that has not previously been perceived. This process is linked to creativity. The process might lead to performing a thought experiment that can be expressed in mathematics (i.e., the language of science). Albert Einstein once stated that the most important aspect of science is imagination. He justified this statement with the observation that human knowledge is limited to what we have learned and been taught, while imagination has no limits. Knowledge is taught in schools from the very beginning through the entire education process and is critical as basic input to feed our imagination. Knowledge is what is known, but the remainder of the natural world is something like a black box about which little is known. We make observations of the natural world in the field and record (i.e., take data) on what processes we believe may be occurring. However, in order to link observation and process, we must first be able to imagine what is possibly happening. For example, I recently made a research trip to Oregon to study a coastal river that has been heavily affected by timber harvesting. The river flows over bedrock that is a mixture of hard, volcanic rock and softer sediments. One of the interesting areas of research in rivers is to better understand how bedrock controls the morphology of river channels and how rivers incise channels into bedrock. At one particular pool that was about 10 m deep, the upstream head of the pool (i.e., the part that is under water at even low summer flow) is a nearly vertical rock wall. The rock juts up from the bottom of the pool to less than 1 m from the surface. Of particular importance to the river and the fisheries resource, which includes salmon, is how these very large pools are formed. We believe they result from scour (i.e., the removal and transport of material from the bed of the river) of rock and sediment, but processes in bedrock rivers are poorly understood.

Immediately upstream from the rock wall and pool is a gravel bar composed of very large particles (about the size of baseballs to basketballs). We would like to know why the gravel doesn't simply fill the pool and thereby stop the river from maintaining the pool. One of the ways of approaching this problem is to imagine that you are a particle, say the size of a baseball, and are moving through the river system and are temporarily stored on the gravel bar upstream of the pool. During high-flow events, the particle, along with many others, is transported by the flowing water from the bar. You might expect the large particles would end up in the 10 m-deep pool. If this happened, the pool would become a deposition site for the particles and would become filled. The pool has been nearly gravel free and in the same location for many years, and it is a well-known salmon-resting pool. In trying to imagine what happens, we must think about the forces that move the particles along the bed of the river and why particles are not trapped within the deep pool. The pool is too large and deep for making detailed current flow measurements and gravel transport measurements at high flow. We can imagine that there must be processes capable of transporting coarse material through the pool. After we have come to the realization that we believe that the coarse particles move from bar to bar and do not become trapped in pools, we can devise experiments and gather data. For example, we can place small tags within the rock particles and use electronic monitoring to track them as they move through the pool. We could also make topographic measurements at low flow and calculate the forces on the particles to provide insight into what the water is doing during the flood stages. The point is, we would not know how to approach this problem were we not able to imagine what is likely to be happening. Observation and calculation would be a step (or level of investigation) in the research to understand how the deep pool is formed and maintained. There is a series of levels from qualitative and descriptive to quantitative analysis, as defined below.

Levels of Investigation. When we approach critical scientific thinking (i.e., disciplined thinking using intellectual standards to help determine the meaning and significance of an idea or argument) and use our imagination and work to solve problems in the natural world, there are several possible levels of investigation:

- Describe the problem and what we think is happening physically in a nonquantitative way. That is, try to describe what is happening in simple terms and ask questions that are hypotheses that may be tested.

- Make measurements and gather data on the processes and materials we are studying. We need to be sure that measurements will exhaustively resolve the questions we are posing. This process could lead to formation of a hypothesis to be tested. The second level, therefore, is the beginning of the quantification process. Quantifying problems and analyzing data provides a deeper level of understanding. Some scientists have stated that, if we are not able to quantify a problem and analyze data associated with it, we do not really understand the problem or process being studied. I would disagree with that statement; however, quantification is necessary to fully understand a problem.
- Monitor our studies through time as much as possible. In the Earth sciences, this is particularly important. When we qualitatively understand what we think is happening and have analyzed data, we integrate our results through time, perhaps to develop a conceptual evolutionary model of how the system under investigation works.

The next step is applying critical thinking. Actually, critical thinking is important in all phases of an investigation.

Thinking Critically. Critical thinking in the sciences, as mentioned earlier, is disciplined thinking, with the objective of determining the meaning and significance of an idea or argument. In order to help think critically, it is useful to consider some intellectual standards to assist us in our thought processes. Some standards can help us with effective communication, clarity, and commitment in acquiring useful skills and knowledge:[16]

- *Significance:* Is the problem we are addressing an important one? Why? For our pool, it is known that salmon need resting places where they can hold during their migration up the river to spawn.
- *Logic:* Do our arguments make sense and follow from the evidence we have collected? Can we show qualitatively and quantitatively that the processes we have imagined to produce a pool or maintain it will do the job?
- *Relevance:* How well is our argument connected to the problem we are investigating? If the problem is pool formation and maintenance, does our argument address that specifically?
- *Breadth:* Have we considered other points of view and looked at the problem at hand from different perspectives? For example, have we separated (in our mind) the question of the gravel not accumulating in the pool from the issue of how the pool is formed?
- *Precision:* Do we understand the degree of exactness to which something is measured? If we are measuring a velocity or distance, what are the errors of measurement? Based on that, can we make more specific measurements or be more exact in our analysis? Is the precision of the measurement adequate for answering the original question?
- *Clarity:* Have we stated our arguments clearly? If we are not clear in our presentation, we will not be able to tell if our argument is relevant or accurate.
- *Fairness:* Have we considered other points of view?

Research involves a lot of reading and study. It may be said that everything is rediscovered each generation, but each generation of scientists brings new thinking and tools (e.g., better instruments of measurement and computer models). For example, G. K. Gilbert, one of the most famous and creative American Earth Scientists, stated qualitatively in the early 1800s how pools might scour at high flow. Field tools (i.e., adequate current meters) for measurement were not yet generally available to quantify his visual observations and qualitative analysis.

Creativity and imagination are important in all aspects of scientific work. If we are to understand the unknown and move science forward, we first must be able to imagine processes and problems with potential avenues to explore them. From this, we develop hypotheses, collect data, and apply our knowledge to better understand how our world works. Unfortunately, teaching creativity and imagination is not possible in any detail. The best advice I can offer is to provide the time you need to think about your work. We often get so involved in the details that we may lose sight of the big picture and not allow our minds to work on a problem and apply imagination. I cannot overemphasize the importance of imagination. The best scientists form their arguments and discussion by starting with something like: "Imagine that you are a particle of sediment that has been loosened by rock weathering in a landslide and moved into a stream channel. Further imagine the processes that will transport you (the particle) toward the ocean, where deposition may take place or processes may transport you further along the coast to enter you into other processes that are operating." All this may sound rather vague, and, unfortunately, this is true. For example, once I was sitting on the bank of a river that was dry at the time, looking at a pool that was scoured to hard compacted gravel (essentially rock). Just downstream was abundant

deposition of coarse gravel, and coarse gravel was also found above the pool. I sat there for hours, trying to imagine how this might occur. It came to me that the gravel, when it's being transported, must move through the pool quickly to be deposited on the next gravel bar downstream. This led to the hypothesis that the tractive forces that move gravel must be greater in the pool at high flow, when sediment is being transported, than on the gravel bars above and below the pool. This led me to the hypothesis that the processes operating at low flow, when the pool was essentially a small pond, were very different from those at high flow when sediment was being transported. I stated this in the form of a hypothesis, namely that tractive forces in pools at high flow exceed those on gravel bars upstream and downstream. I then tested this hypothesis in the small stream by making measurements of velocity of flow over a variety of flow conditions.

Sometimes, imagination and insight come directly in the form of an event that you witness. In North Carolina, over 30 years ago, I was studying a small stream called Mallard Creek. I was looking for pools to study, as I had done in other locations, but there was so much large, woody debris that the pools that I was expecting to find were simply not there. I thought, "What kind of a stream is this? What is all this woody debris about? I can't even find the pools I came here to study." About that time, I heard a large creak and crash and splash about 100 m away and observed a very large hardwood tree falling into the channel. A little light went off in my head, and I realized that this is natural! Large woody debris in forests and streams has a profound effect on channel form and process. That observation and the insight from it, along with work of other scientists, led to a new field that, today, we call *forest geomorphology*. Thousands of papers since the 1970s have been written about how large, woody debris influences channel form and process, as well as its importance for fish habitat. The important point is that in our work and research to understand how our world works, we have to be open to new ideas and use our imagination and critical thinking and hope that we will break new ground—that is, make new discoveries.

- How fast do rivers erode canyons to produce scenic valleys such as Yosemite Valley and the Grand Canyon (**Figure 1.15**)?
- How fast do floodwaters, glaciers, and lava flows move?

As shown in **Table 1.4** (page 32), rates of geologic processes vary from a fraction of a millimeter per year to several kilometers per second. The fastest rates are more than a trillion times the slowest. The most rapid rates, a few kilometers per second, are for events with durations of a few seconds. For example, uplift of 1 m (3.3 ft) during an earthquake may seem like a lot, but when averaged over 1,000 years (the time between earthquakes), it is a long-term rate of 1 mm per year (0.039 in. per year), a typical uplift rate in forming mountains. Of particular importance to environmental geology is that human activities may accelerate the rates of some processes. For example, timber harvesting and urban construction remove vegetation, exposing soils and increasing the rate of erosion. Conversely, the practice of sound soil conservation may reduce rates.

Humans evolved during the Pleistocene epoch (the past 1.65 million years), which is a very small percentage of the age of Earth. To help you conceptualize the geologic time scale, **Figure 1.16** (page 33) illustrates all of geologic time as analogous to yards on a football field. Think back to your high school days, when your star kick-off return player took it deep into your end zone. Assume that the 100-yard field represents the age of Earth (4.6 billion years), making each yard equal to 45 million years. As your star zigs and zags and reaches the 50-yard line, the crowd cheers. But in Earth history he has traveled only 2,250 million years and is still in a primitive oxygen-deficient environment. At the opponent's 45 yard line, free oxygen in the atmosphere begins to support life. As our runner crosses the 12 yard line, the Precambrian period comes to an end, and life becomes much more diversified. At less than half a yard from the goal line, our star runner reaches the beginning of the Pleistocene, the most recent 2.6 million years of Earth history, when humans evolved. As he leaps over the 1 inch line and in for the touchdown, the corresponding period in Earth history is 100,000 years ago, and modern humans were living in Europe. Another way to visualize geologic time is to imagine that 1 calendar year is equal to the age of Earth, 4.6 billion years. In this case, Earth formed on January 1; the first oxygen in the atmosphere did not occur until July; and mammals did not make their appearance until December 18. The first human being arrived on the scene on

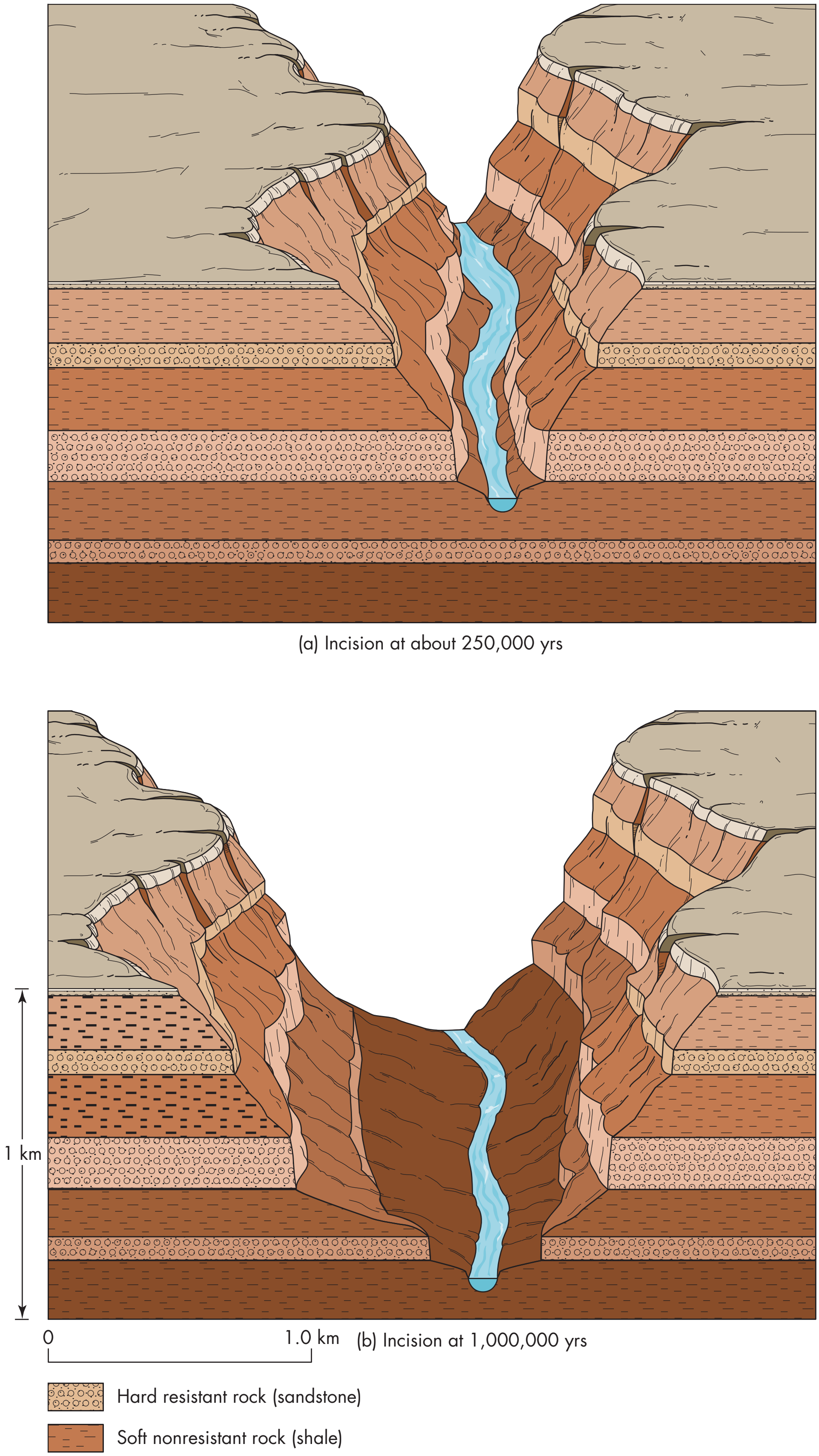


FIGURE 1.15 Eroding a valley Idealized diagram of progressive incision of a river into a sequence of horizontal rocks. The side slope is steep where rocks are hard and resistant to incision, and the rate of incision is generally less than about 0.01 mm per year (about 0.0004 in. per year). For softer rocks, where the side slope is gentle, the rate of incision may exceed 1 mm per year (0.039 in. per year). If the canyon incised about 1 km (0.62 mi) in 1 million years, the average rate is 1 mm per year (0.039 in. per year). *(Modified after King, P. B., and Schumm, S. A., 1980.* The Physical Geography of William Morris Davis. *Norwich, England: Geo Books)*

TABLE 1.4 Some Typical Rates of Geologic Processes

Slow Rates	• Uplift that produces mountains. Generally 0.5 to 2 mm per year (about 0.02 to 0.08 in. per year). Can be as great as 10 mm per year (about 0.39 in. per year). It takes (with no erosion) 1.5 million to 6 million years to produce mountains with elevations of 3 km (around 1.9 mi).
	• Erosion of the land. Generally 0.01 to 1 mm per year (about 0.004 to 0.039 in. per year). It takes (with no uplift) 3 million to 300 million years to erode a landscape by 3 km (about 1.9 mi). Erosion rate may be significantly increased by human activity, such as timber harvesting or agricultural activities that increase the amount of water that runs off the land, causing erosion. Rates of uplift generally exceed rates of erosion, explaining why land above sea level persists.
	• Incision of rivers into bedrock, producing canyons such as the Grand Canyon in Arizona. Incision is different from erosion, which is the material removed over a region. Rates are generally 0.005 to 10 mm per year (about 0.0002 to 0.39 in. per year). Therefore, to produce a canyon 3 km (around 1.9 mi) deep would take 300 thousand to 600 million years. The rate of incision may be increased several times by human activities, such as building dams, because increased downcutting of the river channel occurs directly below a dam.
Intermediate Rates	• Movement of soil and rock downslope by creeping in response to the pull of gravity. Rate is generally 0.5 to 1.2 mm per year (about 0.02 to 0.05 in. per year).
	• Coastal erosion by waves. Generally 0.25 to 1.0 m per year (0.82 to 3.28 ft per year). Thus, to provide 100 years' protection from erosion, a structure should be built about 25 to 100 m (about 82 to 328 ft) back from the cliff edge.
Fast Rates	• Glacier movement. Generally a few meters per year to a few meters per day.
	• Lava flows. Depends on the type of lava and slope. From a few meters per day to several meters per second.
	• River flow in floods. Generally a few meters per second.
	• Debris avalanche, or flow of saturated earth, soil, and rocks downslope. Can be greater than 100 km (62 mi) per hour.
	• Earthquake rupture. Several kilometers per second.

December 31 at 6 P.M.; and recorded history began only 48 seconds before midnight on December 31!

In answering environmental geology questions, we are often interested in the latest Pleistocene (the past 18,000 years), but we are most interested in the past few thousand or few hundred years of the Holocene epoch, which started approximately 10,000 years ago (see Appendix D). Thus, in geologic study, geologists often design hypotheses to answer questions integrated through time. For example, we might want to test the hypothesis that burning fossil fuels, such as coal and oil, which we know releases carbon dioxide into the atmosphere, is causing global warming by trapping heat in the lower atmosphere. We term this phenomenon the *greenhouse effect*, which is discussed in detail in Chapter 18. One way to test this hypothesis would be to show that before the Industrial Revolution, when we started burning a lot of coal and, later, oil to power the new machinery of the time period, the mean global temperature was significantly lower than it is now. We would be particularly interested in the last few hundred to few thousand years before temperature measurements were recorded at various spots around the planet as they are today. To test the hypothesis that global warming is occurring, the investigator could examine prehistoric Earth materials that might provide indicators of global temperature. This examination might involve studying glacial ice or sediments from the bottoms of the oceans or lakes to estimate past levels of carbon dioxide in the atmosphere. Properly completed, studies can provide conclusions that enable us to accept or reject the hypothesis that global warming is occurring.

Our discussion about what science is emphasizes that science is a process. As such, it is a way of knowing that constitutes a current set of beliefs

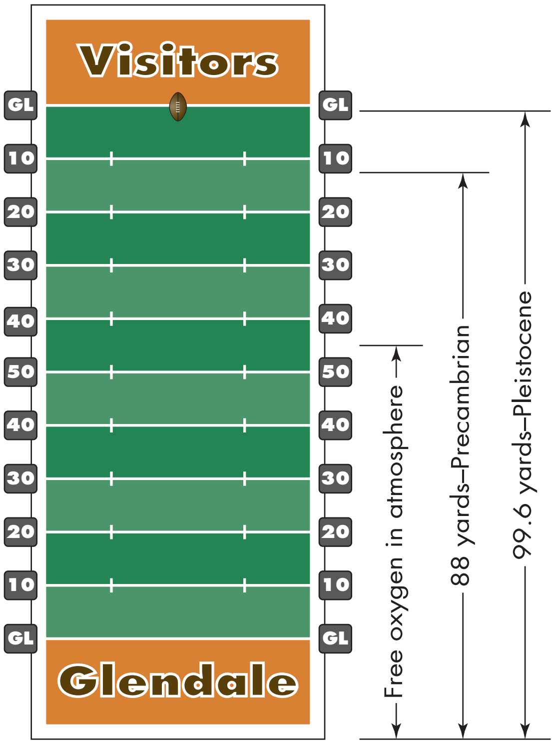


FIGURE 1.16 Time Geologic time as represented by a football field. See the text for further explanation.

based on the application of the scientific method. Science is not the only way a set of beliefs are established. Some beliefs are based on faith, but these, while valid, shouldn't be confused with science. The famous Roman philosopher Cicero once concluded that divine providence, or as we call it now, *intelligent design*, was responsible for the organization of nature and harmony that maintained the environment for all people. As modern science emerged with the process of science, other explanations emerged. This has included explanations for biological evolution by biologists, the understanding of space and time by physicists, and the explanation that continents and ocean basins form through plate tectonics by geologists.

Culture and Environmental Awareness

Environmental awareness involves the entire way of life that we have transmitted from one generation to another. To uncover the roots of our present condition, we must look to the past to see how our culture and our political, economic, ethical, religious, and aesthetic institutions affect the way we perceive and respond to our physical environment.

An ethical approach to maintaining the environment is the most recent development in the long history of human ethical evolution. A change in the concept of property rights has provided a fundamental transformation in our ethical evolution. In earlier times, human beings were often held as property, and their masters had the unquestioned right to dispose of them as they pleased. Slaveholding societies certainly had codes of ethics, but these codes did not include the idea that people cannot be property. Similarly, until very recently, few people in the industrialized world questioned the right of landowners to dispose of land as they please. Only within this century has the relationship between civilization and its physical environment begun to emerge as a relationship involving ethical considerations.

Environmental (including ecological and land) ethics involves limitations on social as well as individual freedom of action in the struggle for existence in our stressed environment. A **land ethic** assumes that we are responsible not only to other individuals and society but also to the total environment, the larger community consisting of plants, animals, soil, rocks, atmosphere, and water. According to this ethic, we are the land's citizens and protectors, not its conquerors. This role change requires us to revere, love, and protect our land rather than allow economics to determine land use.[17] The creation of national parks and forests is an example of protective action based on a land ethic. Yellowstone National Park in Wyoming and Montana was the first national park in the United States, established in March 1872. Later, the United States created other national parks, monuments, and forests to preserve some of the country's most valued aesthetic resources. Trees, plants, animals, and rocks are protected within the bounds of a national park or forest. In addition, rivers flow free and clean, lakes are not overfished or polluted, and mineral resources are protected. Finally, the ethic that led to the protection of such lands allows us the privilege of enjoying these natural areas and ensures that future generations will have the same opportunity.

We will now change focus to discuss why solving environmental problems tends to be difficult and introduce the emerging environmental policy tool known as the precautionary principle.

A Closer Look

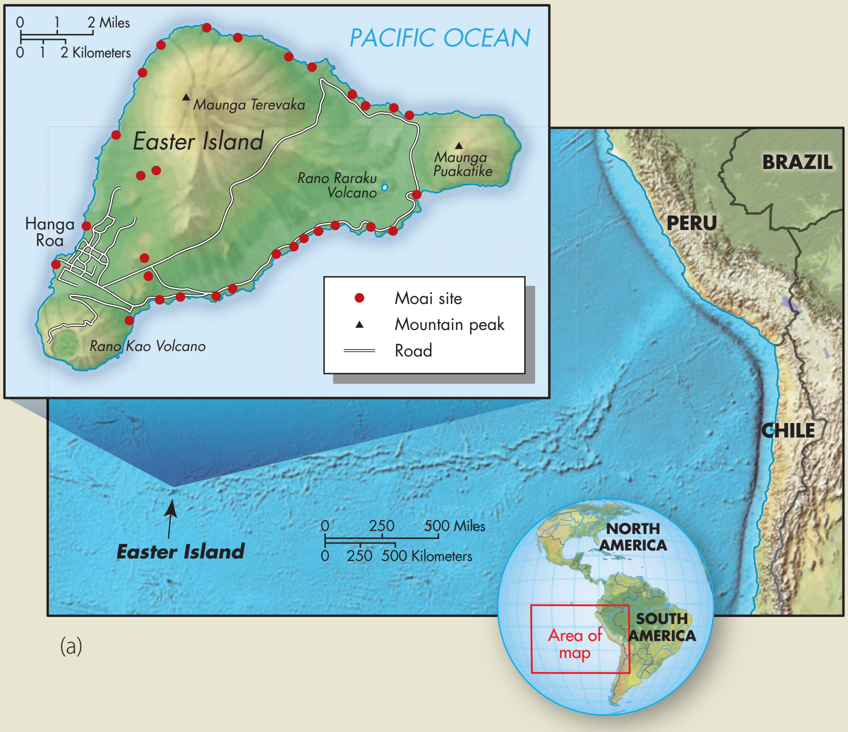
Easter Island: A Complex Problem to Understand

Easter Island, at 140 km^2, is a small, triangular-shaped, volcanic island located several thousand kilometers west of South America, with a subtropical climate (**Figure 1.Da**). Polynesian people first reached the island approximately 1,500 years ago. When the Polynesians first arrived, they were greeted by a green island covered with forest, including large palm trees. By the sixteenth century, 15,000 to 30,000 people were living there. They had established a complex society spread among small villages, and they raised crops and chickens to supplement the fish, marine mammals, and seabirds that sustained their diet. For religious reasons, they carved massive statues (called moai) from volcanic rock (Figure 1.D). The statues have the form of a human torso with a stone headdress. Most are about 7 m high (21 ft), but some are higher than 20 m. The statues were moved into place at various locations on the island using ropes, with tree trunks as rollers.

When Europeans reached Easter Island in the seventeenth century, only about 2,000 people were living on the island. The main symbols of the once-vibrant civilization were the statues, most of which had been toppled and damaged. No trees were growing on the island, and the people were living in a degraded environment.

Why Did the Society Collapse?

Evidently, Easter Island society collapsed in just a few decades, probably as a result of degradation of the island's limited resource base. As the human population of the island increased, more and more land was cleared for agriculture, and the re-



(a)

(b)

FIGURE 1.D Easter Island (a) Map showing the location and geography of Easter Island. (b) Statues called moai, which were carved from stone. *(Alexander Chaikin/Shutterstock)*

maining trees were used for fuel and for moving the statues into place. Previously, the soils had been protected beneath the forest cover and had held water in the subtropical environment. Soil nutrients had probably been supplied by dust from thousands of kilometers away that reached the island on the winds. Once the forest was cleared, the soils eroded, and the agricultural base of the society was diminished. Loss of the forest also resulted in loss of forest products necessary for building homes and boats, and, as a result, the people were forced to live in caves. Without boats, they could no longer rely on fish as a source of protein. As population pressure increased, wars between villages became common, as did slavery and even cannibalism, in attempts to survive in an environment depleted of its resource base.[18]

Lessons Learned. The story of Easter Island is a dark one that vividly points to what can happen when an isolated area is deprived of its resources through human activity: Limited resources cannot support an ever-growing human population.

The people of Easter Island depleted their resources, because they failed to understand and recognize a number of factors. Easter Island has a naturally fragile environment[18–22] compared to many other islands the Polynesians colonized:

- The island is small and very isolated. The inhabitants couldn't expect help in hard times from neighboring islands.
- Volcanic soils were originally fertile, but agricultural erosion was a problem, and soil-forming processes on the island were slow compared to those on more tropical islands. Nutrient input to soils from atmospheric dust from Asia was not significant.
- The island's three volcanoes (see Figure 1.Da) are not active, so no fresh volcanic ash added nutrients to the soils. The topography is low, with gentle slopes. Steep high mountains generate clouds, rain, and runoff that nourish lowlands.
- With a subtropical climate with annual rainfall of 80 cm (50 in.), there was sufficient rainfall, but the water quickly infiltrated through the soil into porous volcanic rock.
- There are no coral reefs near Easter Island to provide abundant marine resources.

There is fear today that our planet, an isolated island in space, may be reaching the same threshold faced by the people of Easter Island in the sixteenth century. In the twenty-first century, we are facing limitations of our resources in a variety of areas, including soils, freshwater, forests, rangelands, and ocean fisheries. The primary question from both an environmental perspective and for the history of humans on Earth is: Will we recognize the limits of Earth's resources before it is too late to avoid the collapse of human society on a global scale? Today, there are no more frontiers on Earth, and we have a nearly fully integrated global economy. With our modern technology, we have the ability to extract resources and transform our environment at rates much faster than any people before us. The major lesson from Easter Island is clear: Develop a sustainable global economy that ensures the survival of our resource base and other living things on Earth or suffer the consequences.[18]

Some aspects of the history of Easter Island have recently been challenged as being only part of the story. Deforestation certainly played a role in the loss of the trees, and rats that arrived with the Polynesians were evidently responsible for eating seeds of the palm trees, not allowing regeneration. The alternative explanation is that the Polynesian people on Easter Island at the time of European contact in 1722 numbered about 3,000 persons. This population may have been close to the maximum reached in about the year 1350. Following contact, introduced diseases and enslavement resulted in reduction of the population to about 100 by the late 1870s.[19,22] As more of the story of Easter Island emerges from scientific and social studies, the effects of human resource exploitation, invasive rats, and European contact will become clearer. The complex processes that led to the collapse will hopefully lead to a better understanding of how we can sustain our global human culture.

Why Is Solving Environmental Problems So Difficult?

Many environmental problems tend to be complex and multifaceted. They may involve issues related to physical, biological, and human processes (see A Closer Look: Easter Island: A Complex Problem to Understand). Some of the problems are highly charged from an emotional standpoint, and potential solutions are often vigorously debated.

Solving environmental problems may be difficult for three main reasons:

- Expediential growth is often encountered. Expediential growth means that the amount of change may be happening quickly, whether

we are talking about an increase or a decrease.

- There are often lag times between when a change occurs and when it is recognized as a problem. If the lag time is long, it may be very difficult to even recognize a particular problem.
- An environmental problem involves the possibility of irreversible change. If a species becomes extinct, it is gone forever.

Environmental policy links to environmental economics are in their infancy. That is, the policy framework to solve environmental problems is a relatively new arena. We are developing policies such as the precautionary principle and finding ways to evaluate the economics of gains and losses from environmental change. For example, how do you put a dollar amount on aesthetics or living in a quality environment? Such an analysis often comes down to an exercise in values clarification. Science can provide a number of potential solutions to problems, but which solution we pick depends upon our values.

Precautionary Principle

What Is the Precautionary Principle? Science has the role of trying to understand physical and biological processes associated with environmental problems, such as global warming, exposure to toxic materials, and depletion of resources, among others. However, all science is preliminary, and it is difficult to prove relationships between physical and biological processes and link them to human processes. Partly for this reason, in 1992, the Rio Earth Summit on sustainable development supported the **precautionary principle**. The idea behind the principle is that when there exists a potentially serious environmental problem, scientific certainty is not required to take a precautionary approach. In other words, it is better to be safe than sorry. The precautionary principle thus contributes to the critical thinking on a variety of environmental concerns, such as manufacture and use of toxic chemicals or burning of huge amounts of coal as oil becomes scarcer. It is considered one of the most influential ideas for obtaining an intellectual, environmentally just policy framework for environmental problems.[23]

The precautionary principle recognizes that scientific proof is not possible in most instances, and management practices are needed to reduce or eliminate environmental problems believed to result from human activities. In other words, in spite of the fact that full scientific certainty is not available, we should still take cost-effective action to solve environmental problems.

The Precautionary Principle May Be Difficult to Apply. One of the difficulties in applying the precautionary principle is the decision concerning how much scientific evidence is needed before action on a particular problem should be taken. This is a significant and often controversial question. An issue being considered has to have some preliminary data and conclusions but awaits more scientific data and analysis. For example, when considering environmental health issues related to burning coal, there may be an abundance of scientific data about air, water, and land pollution, but with gaps, inconsistencies, and other scientific uncertainties. Those in favor of continuing or increasing the use of coal may argue that there is not sufficient proof to warrant restricting its use. Others would argue that absolute proof of safety is necessary before a big increase in burning of coal is allowed. The precautionary principle, applied to this case, would be that lack of full scientific certainty concerning the use of coal should not be used as a reason for not taking, or postponing, cost-effective measures to reduce or prevent environmental degradation or heath problems. This raises the question of what constitutes a cost-effective measure. Determination of benefits and costs of burning more coal compared to burning less or treating coal more to clean up the fuel should be done, but other economic analysis may also be appropriate.[23,24]

There will be arguments over what constitutes sufficient scientific knowledge for decision making. The precautionary principle may be difficult to apply, but it is becoming a common part of the process of environmental analysis and policy when applied to environmental protection and environmental health issues. The European Union has been applying the principle for over a decade, and the City and County of San Francisco in 2003 became the first government in the United States to make the precautionary principle the basis for its environmental policy.

Applying the precautionary principle requires us to use the principle of environmental unity and predict potential consequences of activities before they occur. Therefore, the precautionary principle has the potential to become a proactive, rather than reactive, tool in reducing or eliminating environmental degradation resulting from human activity. The principle

moves the burden of proof of no harm from the public to those proposing a particular action. Those who develop new chemicals or actions are often, but not always, against the precautionary principle. The opponents often argue that applying the principle is too expensive and will stall progress. It seems unlikely that the principle will be soon applied across the board in the United States to potential environmental problems. Nevertheless, it will likely be invoked more often in the future. When the precautionary principle is applied, it must be an honest debate between all informed and potentially affected parties. The entire range of alternative actions should be considered, including taking no action.

Science and Values

We Are Creatures of the Pleistocene. There is no arguing that we are a very successful species that until recently has lived in harmony with both our planet and other forms of life for over 100,000 years. We think of ourselves as modern people, and, certainly, our grasp of science and technology has grown tremendously in the past several hundred years. However, we cannot forget that our genetic roots are in the Pleistocene. In reality, our deepest beliefs and values are probably not far distant from those of our ancestors who sustained themselves in small communities, moving from location to location and hunting and gathering what they needed. At first thought, this statement seems inconceivable and not possible to substantiate, considering the differences between our current way of life and that of our Pleistocene ancestors. It has been argued that studying our Pleistocene ancestors, with whom we share nearly identical genetic information, may help us understand ourselves better.[25] That is, much of our human nature and, in fact, our very humanity may be found in the lives of the early hunters and gatherers, explaining some of our current attitudes toward the natural world. We are more comfortable with natural sounds and smells, like the movement of grass where game is moving or the smell of ripe fruit, than the shrill noise of horns and jackhammers and the smell of air pollution in the city. Many of us enjoy sitting around a campfire, roasting marshmallows and telling stories about bears and rattlesnakes. We may find a campfire comforting even if smoke stings our eyes because our Pleistocene ancestors knew fire protected them from predators, such as bears, wolves, and lions. If you want to liven up a campfire talk, start telling grizzly bear stories!

Solutions we choose to solve environmental problems depend upon how we value people and the environment. For example, if we believe that human population growth is a problem, then conscious decisions to reduce human population growth reflect a value decision that we as a society choose to endorse and implement. As another example, consider flooding of small urban streams. Flooding is a hazard experienced by many communities. Study of rivers and their natural processes leads to a number of potential solutions for a given flood hazard. We may choose to place the stream in a concrete box—a remedy that can significantly reduce the flood hazard. Alternatively, we may choose to restore our urban streams and their floodplains, the flat land adjacent to the river that periodically floods, as greenbelts. This choice will reduce damage from flooding, while providing habitat for a variety of animals, including raccoons, foxes, beavers, and muskrats that use the stream environment; resident and migratory birds that nest, feed, and rest close to a river; and a variety of fish that live in the river system. We will also be more comfortable when interacting with the river. That is why river parks are so popular.

The coastal environment, where the coast line and associated erosional processes come into conflict with development, provides another example for science and values. Solutions to coastal erosion may involve defending the coast, along with its urban development, at all cost by constructing “hard structures,” such as seawalls. Science tells us that consequences from the hard solution generally include reduction or elimination of the beach environment in favor of protecting development. Science also tells us that using appropriate setbacks from the erosion zone of coastal processes provides a buffer zone from the erosion, while maintaining a higher quality coastal environment that includes features such as beaches and adjacent sea cliffs or dune lines. The solution we pick depends upon how we value the coastal zone. If we value the development more than the beach, then we may choose to protect development at all cost. If we value the beach environment, we may choose more flexible options that allow for erosion to take place naturally within a buffer zone between the coast and development.

By the year 2050, the human population on our planet will likely increase to about 9 billion people,

about 2 billion more than today. Thus, it appears that during the next 50 years, crucial decisions must be made concerning how we will deal with the increased population associated with increased demands on resources including land, water, minerals, and air. The choices we make will inevitably reflect our values.

Making The Connection

Linking the Opening Case History About Hispaniola to the Fundamental Concepts

Consider and discuss the following questions:

1. What are some linkages between the history of the country of Haiti and why environmental degradation occurred there?
2. Why are the people of Haiti so vulnerable to hazards such as earthquakes and hurricanes?
3. What are analogies or parallel developments between Haiti and Easter Island? Are such comparisons valid?

Summary

The immediate causes of the environmental crisis are overpopulation, urbanization, and industrialization, which have occurred with too little ethical regard for our land and inadequate institutions to cope with environmental stress. Solving environmental problems involves both scientific understanding and the fostering of social, economic, and ethical behavior that allows solutions to be implemented. Beyond this, complex environmental problems can be difficult to solve, due to the possibility of exponential growth, lag times between cause and effect, and irreversible consequences. A new emerging policy tool is the precautionary principle. The idea behind the principle is that when a potentially serious environmental problem exists, scientific certainty is not required to take a precautionary approach and find a cost-efficient solution. Some environmental problems are sufficiently serious that it is better to be safe than sorry.

Five fundamental concepts establish a philosophical framework for our investigation of environmental geology:

1. The increasing world population is the number-one environmental problem.
2. Sustainability is the preferred solution to many environmental problems.
3. Having an understanding of the Earth system and rates of change in systems is critical to solving environmental problems.
4. Earth processes that are hazardous to people have always existed. These natural hazards must be recognized and avoided when possible, and their threat to human life and property minimized.
5. Results of scientific inquiry to solve a particular environmental problem often result in a series of potential solutions consistent with the scientific findings. Which solution we choose reflects our value system.

Key Terms

Review Questions

1. What is environmental geology?
2. Define the components of the scientific method.
3. What are the roots of the so-called environmental crisis?
4. Why are we so concerned about the increase in human population?
5. What is sustainability?
6. Define the principle of environmental unity and provide a good example.
7. What is exponential growth?
8. What is Earth systems science, and why is it important?
9. What do we mean by average residence time?
10. How can the principle of uniformitarianism be applied to environmental geology?
11. What is the Gaia hypothesis?
12. What is the precautionary principle and why is it important?
13. Why is solving complex environmental problems often difficult?

Critical Thinking Questions

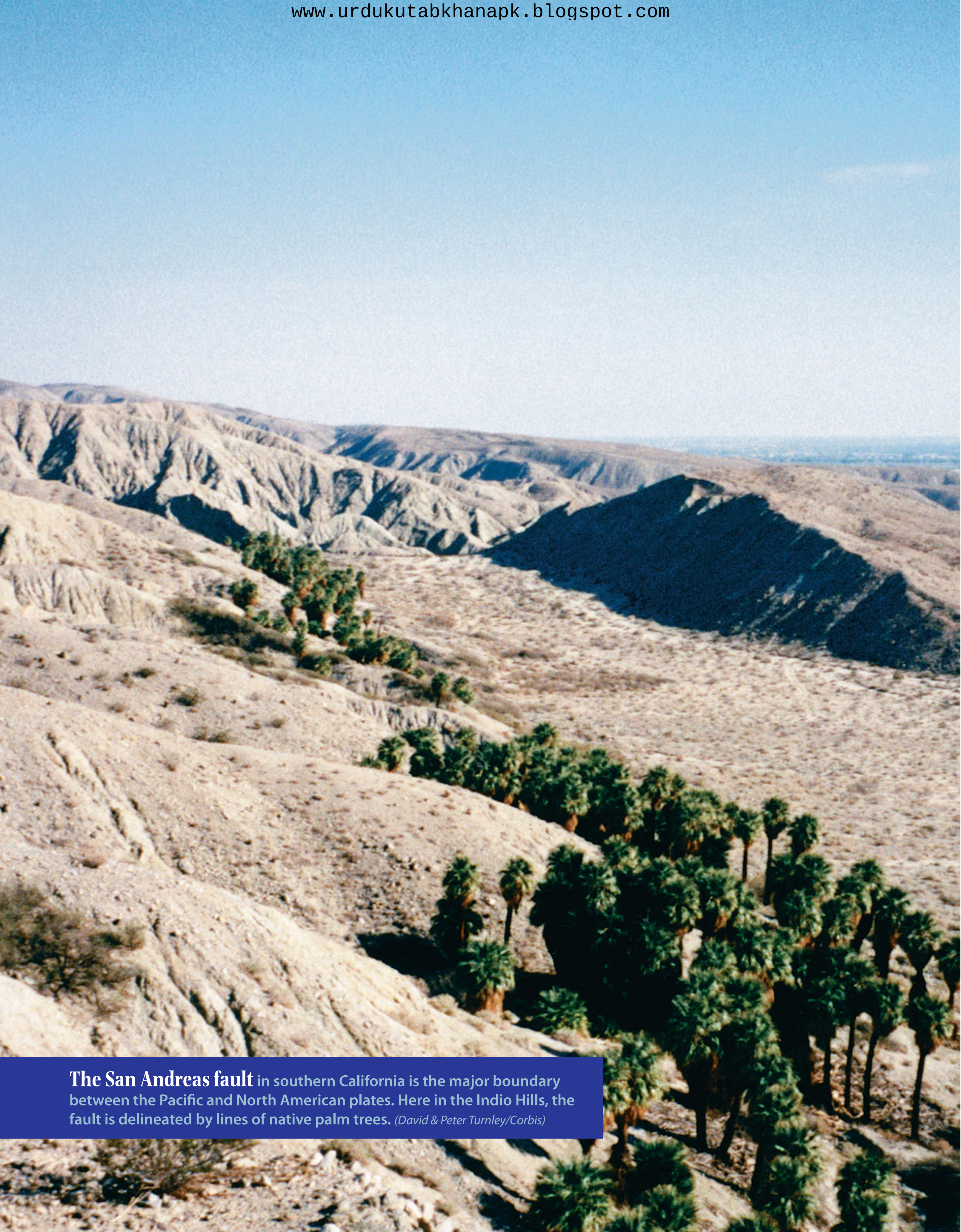
1. Assuming that there is an environmental crisis today, what possible solutions are available to alleviate the crisis? How will solutions in developing countries differ from those in highly industrialized societies? Will religion or political systems have a bearing on potential solutions? If so, how will they affect the solutions?
2. It has been argued that we must control human population because otherwise we will not be able to feed everyone. Assuming that we could feed 10 billion to 15 billion people on Earth, would we still want to have a smaller population than that? Why?
3. We state that sustainability is the environmental objective. Construct an argument to support this statement. Are the ideas of sustainability and building a sustainable economy different in developing, poor countries than in countries that are affluent and have a high standard of living? How are they different, and why?
4. The concept of environmental unity is an important one today. Consider some major development being planned for your region and outline how the principle of environmental unity could help in determining the project's potential environmental impact. In other words, consider a development and then a series of consequences resulting from it. Some of the impacts may be positive and some may be negative in your estimation.
5. Do you believe we have a real connection to our Pleistocene ancestors? Could such a connection explain our childlike love of baby animals or the storytelling around a campfire? Is the human race's long history of hunting and gathering, during which our genetic evolution occurred, reflected in our values?
6. Is the Gaia hypothesis science? How could you test the main parts? Which would be hard to test? Why?
7. Defend or criticize the notion that increase in human population is *the* environmental problem and that sustainability is the solution.
8. Do you think the precautionary principle should be applied to the problem of controlling the growth of the human population? If you do, how could it be applied?

Companion Website

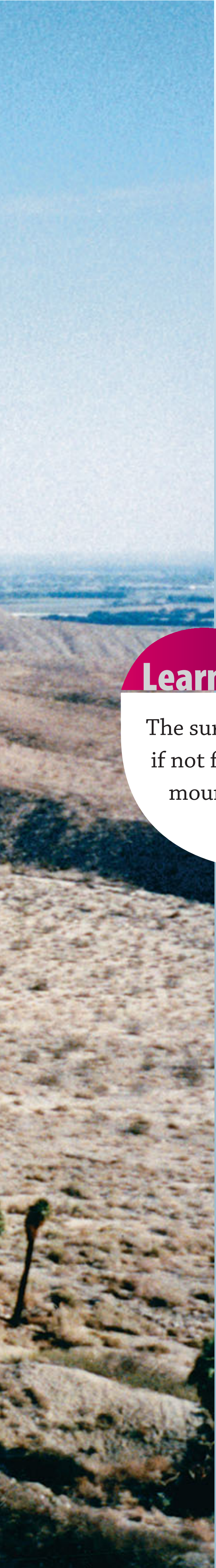
www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.



The San Andreas fault in southern California is the major boundary between the Pacific and North American plates. Here in the Indio Hills, the fault is delineated by lines of native palm trees. *(David & Peter Turnley/Corbis)*



2

Internal Structure of Earth and Plate Tectonics

Written with the assistance of Tanya Atwater

Learning Objectives

The surface of Earth would be much different—relatively smooth, with monotonous topography—if not for the active tectonic processes within Earth that produce earthquakes, volcanoes, mountain chains, continents, and ocean basins.[1] In this chapter, we focus directly on the interior of Earth, with the following learning objectives:

- **Understand the basic internal structure and processes of Earth**
- **Understand the basic ideas behind and evidence for the theory of plate tectonics**
- **Understand the mechanisms of plate tectonics**
- **Understand the relationship of plate tectonics to environmental geology**

Case History

Two Cities on a Plate Boundary

California straddles the boundary between two tectonic plates, which are discussed in detail in this chapter. That boundary between the North American and Pacific plates is the notorious San Andreas fault (**Figure 2.1**). A *fault* is a fracture along which one side has moved relative to the other, and the San Andreas fault is a huge fracture zone, hundreds of kilometers long. Two major cities, Los Angeles to the south and San Francisco to the north, are located on opposite sides of this fault. San Francisco was nearly destroyed by a major earthquake in 1906, which led to the identification of the fault. Many of the moderate to large earthquakes in the Los Angeles area are on faults related to the San Andreas fault system. Most of the beautiful mountain topography in coastal California near both Los Angeles and San Francisco is a direct result of processes related to movement on the San Andreas fault. However, this beautiful topography comes at a high cost to society. Since 1906, earthquakes on the San Andreas fault system or on nearby faults, undoubtedly influenced by the plate boundary, have cost hundreds of lives and many billions of dollars in property damage. Construction of buildings, bridges, and other structures in California is more expensive than elsewhere because these structures must be designed to withstand ground shaking caused by earthquakes. Older structures have to be *retrofitted*, or have changes made to their structure, to withstand the shaking, and many people purchase earthquake insurance in an attempt to protect themselves from the "big one."

Los Angeles is on the Pacific plate and is slowly moving toward San Francisco, which is on the North American plate. In about 20 million years, the cities will be side by side. If people are present, they might be arguing over which city is a suburb of the other. Of course, there will still be a plate boundary between the Pacific and North American plates 20 million years from now, because large plates have long geologic lives. However, the boundary may not be the San Andreas fault. The plate boundary will probably have moved eastward, and the topography of what is now California may be somewhat different. In fact, some recent earthquake activity in California, such as the large 1992 Landers earthquake, east of the San Andreas fault, may be the beginning of a shift in the plate boundary.

2.1 Internal Structure of Earth

You may be familiar with the situation comedy *Third Rock from the Sun*, a phrase that refers to our planet Earth. Far from being a barren rock, Earth is a complex dynamic planet that in some ways resembles a chocolate-covered cherry. That is, Earth has a rigid outer shell, a solid center, and a thick layer of liquid in between the two that moves around as a result of dynamic internal processes. The internal processes are incredibly important in affecting the surface of Earth. They are responsible for the largest landforms on the surface: continents and ocean basins. The configuration of the continents and ocean basins in part controls the oceans' currents and the distribution of heat carried by seawater in a global system that affects climate, weather, and the distribution of plant and animal life on Earth. Finally, Earth's internal processes are also responsible for regional landforms, including mountain chains, chains of active volcanoes, and large areas of elevated topography, such as the Tibetan Plateau and the Rocky Mountains. The high topography that includes mountains and plateaus significantly affects both global circulation patterns of air in the lower atmosphere and climate, thereby directly influencing all life on Earth. Thus, our understanding of the internal processes of Earth is of much more than simply academic interest. These processes are at the heart of producing the multitude of environments shared by all living things on Earth.

The Earth Is Layered and Dynamic. Earth (**Figure 2.2a**, page 44) has a radius of about 6,300 km (4,000 mi) (Figure 2.2b). Information

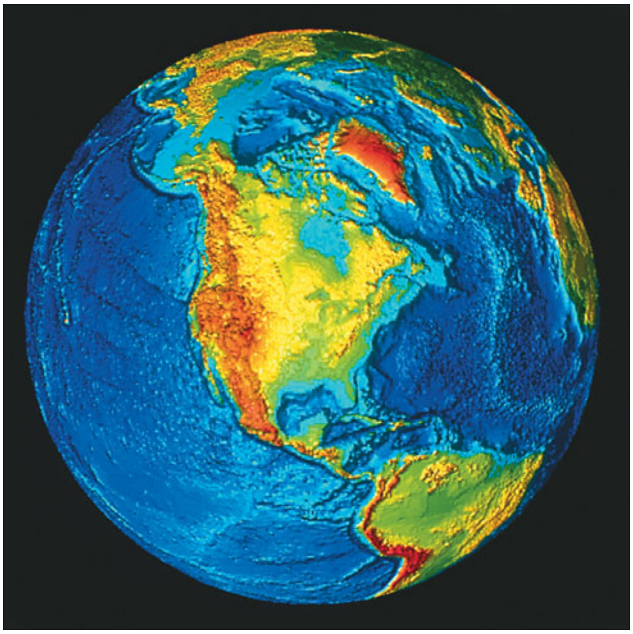
FIGURE 2.1 San Andreas fault Map showing the San Andreas fault and topography in California. Arrows show relative motion on either side of the fault. *(R. E. Wallace/National Earthquake Information Center, USGS)*

regarding the internal layers of the Earth is shown in Figure 2.2b. We can consider the internal structure of Earth in two fundamental ways:

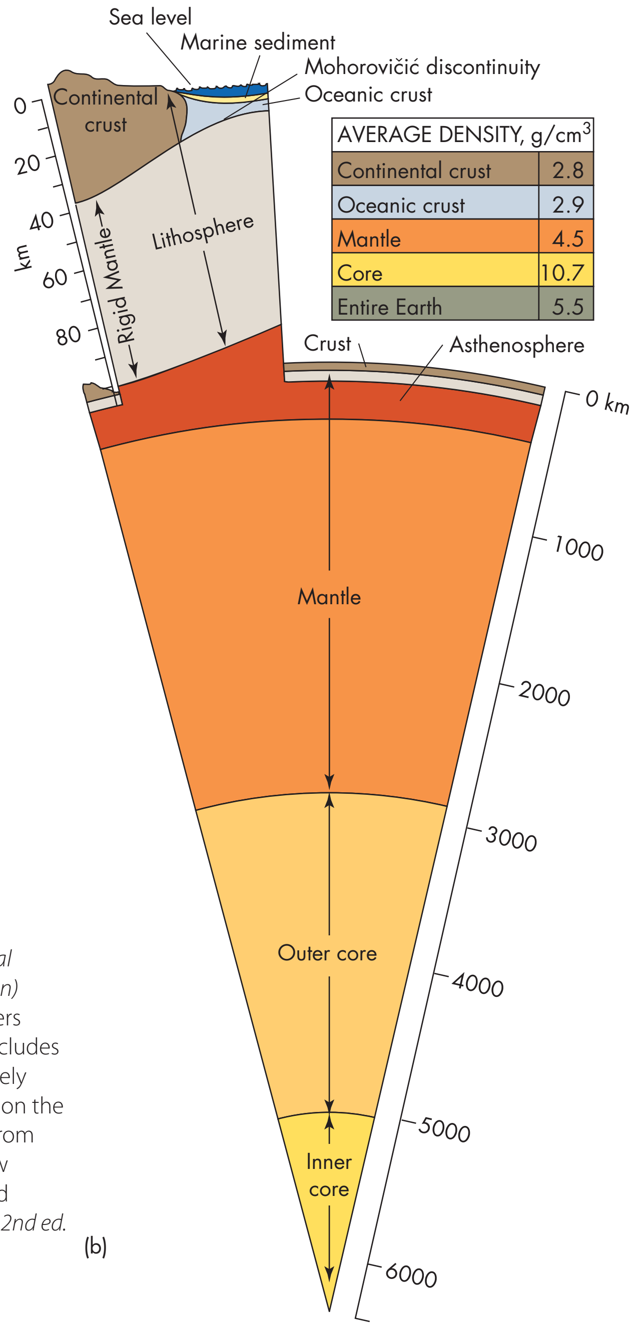
- By composition and density (heavy or light)
- By physical properties (e.g., solid or liquid, weak or strong)

Our discussion will explore the two ways of looking at the interior of our planet. Some of the components of the basic structure of Earth[1] are:

- A solid inner **core** with a thickness of more than 1,300 km (808 mi) that is roughly the size of the moon but with a temperature about as high as the temperature of the surface of the Sun.[2] The inner core is believed to be primarily metallic, composed mostly of iron (about 90 percent by weight), with minor amounts of elements such as sulfur, oxygen, and nickel.
- A liquid outer core with a thickness of just over 2,000 km (1,243 mi), with a composition similar to that of the inner core. The outer core is very fluid, more similar to water than to honey. The average density of the inner core and outer core is approximately 10.7 g/cm^3 (0.39 lb/in.^{3}). The maximum near the center of Earth is about 13 g/cm^3 (0.47 lb/in.^{3}). By comparison, the density of water is 1 g/cm^3 (0.04 lb/in.^{3}) and the average density of Earth is approximately 5.5 g/cm^3 (0.2 lb/in.^{3}).
- The **mantle**, nearly 3,000 km (1,864 mi) thick, surrounds the outer core and is mostly solid, with an average density of approximately 4.5 g/cm^3 (0.16 lb/in.^{3}). Rocks in the mantle are



(a)



(b)

FIGURE 2.2 Earth and its interior (a) Earth from space. *(National Geophysical Data Center, National Oceanic and Atmospheric Administration)* (b) Idealized diagram showing the internal structure of Earth and its layers extending from the center to the surface. Notice that the lithosphere includes the crust and part of the mantle, and the asthenosphere is located entirely within the mantle. Properties of the various layers have been estimated on the basis of (1) interpretation of geophysical data (primarily seismic waves from earthquakes); (2) examination of rocks thought to have risen from below by tectonic processes; and (3) meteorites, thought to be pieces of an old Earthlike planet. *(From Levin, H. L. 1986.* Contemporary Physical Geology, *2nd ed. Philadelphia: Saunders)*

primarily iron- and magnesium-rich silicates. Interestingly, the density difference between the outer core and the overlying mantle is greater than that between the rocks at the surface of Earth and the overlying atmosphere! In the case of the outer core and mantle, the more fluid phase of the outer core is beneath the solid phase of the mantle. This is just the opposite of the case of the rock–atmosphere relationship, where the fluid atmosphere overlies the solid lithosphere. Because it is liquid, the outer core is dynamic and greatly influences the overlying mantle and, thus, the surface of Earth.

- The **crust**, with variable thickness, is the outer rock layer of the Earth. The boundary between the mantle and crust is known as the Mohorovičić discontinuity (also called the **Moho**). It separates the lighter rocks of the crust with an average density of approximately 2.8 g/cm^3 (0.10 lb/in.^{3}) from the denser rocks of the mantle below.

Continents and Ocean Basins Have Significantly Different Properties and History. Within the uppermost portion of the mantle, near the surface of Earth, our terminology becomes more complicated. For example, the cool, strong outermost layer of Earth is also called the **lithosphere** (*lithos* means "rock"). It is much stronger and more rigid than the material underlying it, the **asthenosphere** (*asthenos* means "without strength"), which is a hot and slowly flowing layer of relatively weak rock. The lithosphere averages about 100 km (62 mi) thick, ranging from a few kilometers (1 to 2 mi) thick beneath the crests of mid-oceanic ridges to about 120 km (75 mi) beneath ocean basins and 20 to 400 km (13 to 250 mi) beneath the continents. The crust is embedded in the top of the lithosphere. Crustal rocks are less dense than the mantle rocks below, and oceanic crust is slightly denser than continental crust. Oceanic crust is also thinner: The ocean floor has a uniform crustal thickness of about 6 to 7 km (3.7 to 4.4 mi), whereas the crustal thickness of continents averages about 35 km (22 mi) and may be up to 70 km (44 mi) thick beneath mountainous regions. Thus, the average crustal thickness is less than 1 percent of the total radius of Earth and can be compared to the thin skin of a tangerine. Yet it is this layer that is of particular interest to us because we live at the surface of the continental crust.

In addition to differences in density and thickness, the continental and oceanic crusts have very different geologic histories. The oceanic crust of the present ocean basins is less than approximately 200 million years old, whereas the continental crust may be several billion years old. Three thousand kilometers (1,865 mi) below us, at the core–mantle boundary, processes may be occurring that significantly affect our planet at the surface. It has been speculated that gigantic cycles of convection occur within Earth's mantle, rising from as deep as the core–mantle boundary up to the surface and then falling back again. The concept of **convection** is illustrated by heating a pan of hot water on a stove (**Figure 2.3**). Heating the water at the bottom of the pan causes the water to become less dense and more unstable, so it rises to the top. The rising water displaces denser, cooler water, which moves laterally and sinks to the bottom of the pan. It is suggested that Earth layers contain convection cells and operate in a similar fashion.

A complete convection cycle in the mantle may take as long as 500 million years.[1] Mantle convection is fueled at the core–mantle boundary both by heat supplied from the molten outer core of Earth and by radioactive decay of elements (such as uranium) scattered throughout the mantle. Let us now examine some of the observations and evidence that reveal the internal structure of Earth.

2.2 How We Know About the Internal Structure of Earth

What We Have Learned About Earth from Earthquakes. Our knowledge concerning the structure of Earth's interior arises primarily from our study of **seismology**. Seismology is the study of earthquakes and the passage of seismic waves through Earth.[3] When a large earthquake occurs, seismic energy is released and seismic waves move both through Earth and along its surface. The properties of these waves are discussed in detail in Chapter 6 with earthquake hazards.

Some waves move through solid and liquid materials, while others move through solid, but not liquid, materials. The rates at which seismic waves

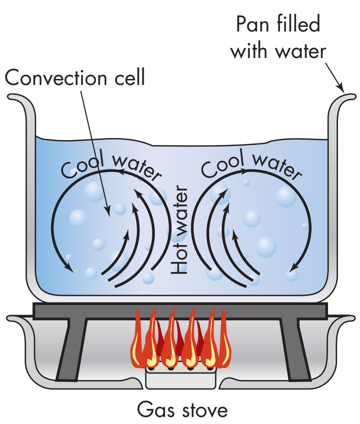


FIGURE 2.3 Convection Idealized diagram showing the concept of convection. As the pan of water is heated, the less dense hot water rises from the bottom to displace the denser cooler water at the top, which then sinks down to the bottom. This process of mass transport is called *convection*, and each circle of rising and falling water is a convection *cell*.

propagate are on the order of a few kilometers per second (1 or 2 mi per second). Their actual velocity varies with the properties of the materials through which the waves are propagating (i.e., moving). When the seismic waves encounter a boundary, such as the mantle–core boundary, some of them are *reflected* back. Others cross the boundary and are *refracted* (i.e., change the direction of propagation). Still others fail to propagate through the liquid outer core. Thousands of seismographs (i.e., instruments that record seismic waves) are stationed around the world. When an earthquake occurs, the reflected and refracted waves are recorded when they emerge at the surface. Study of these waves has been a powerful tool for deducing the layering of the interior of Earth and the properties of the materials found there.

In summary, the boundaries that delineate the internal structure of Earth are determined by studying seismic waves generated by earthquakes and recorded on seismographs around Earth. As seismology has become more sophisticated, we have learned more and more about the internal structure of Earth and are finding that the structure can be quite variable and complex. For example, we have been able to recognize the following:

- Where magma, which is molten rock beneath Earth's surface, is generated in the asthenosphere
- The existence of slabs of lithosphere that have apparently sunk deep into the mantle
- The extreme variability of lithospheric thickness, reflecting its age and history

2.3 Plate Tectonics

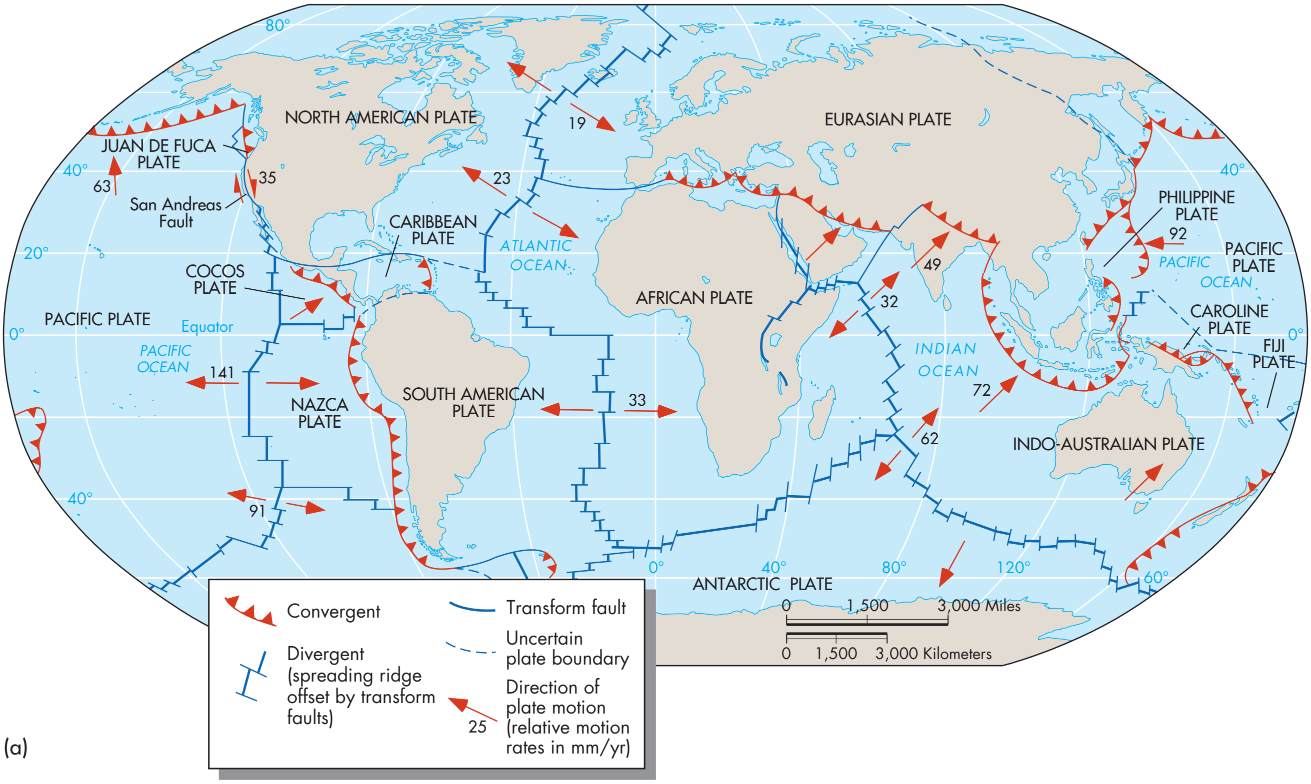
The term *tectonics* refers to the large-scale geologic processes that deform Earth's lithosphere, producing landforms such as ocean basins, continents, and mountains. Tectonic processes are driven by forces within the Earth. These processes are part of the tectonic system, an important subsystem of the Earth system.

Movement of the Lithospheric Plates

What Is Plate Tectonics? The lithosphere is broken into large pieces called *lithospheric plates* that move relative to one another (**Figure 2.4a**).[4] Processes associated with the creation, movement, and destruction of these plates are collectively known as **plate tectonics**.

Locations of Earthquakes and Volcanoes Define Plate Boundaries. A lithospheric plate may include both a continent and part of an ocean basin or an ocean region alone. Some plates are very large, and some are relatively small, though they are significant on a regional scale. For example, the Juan de Fuca plate off the Pacific Northwest coast of the United States, which is relatively small, is responsible for many of the earthquakes in northern California. The boundaries between lithospheric plates are geologically active areas. Most earthquakes and many volcanoes are associated with these boundaries. In fact, plate boundaries are defined by the areas in which concentrated seismic activity occurs (Figure 2.4b). Over geologic time, plates are formed and destroyed, cycling materials from the interior of Earth to the surface and back again at these boundaries (**Figure 2.5**, page 48). The continuous recycling of tectonic processes is collectively called the *tectonic cycle*.

Seafloor Spreading Is the Mechanism for Plate Tectonics. As the lithospheric plates move over the asthenosphere, they carry the continents embedded within them.[5] The idea that continents move is not new; it was first suggested by German scientist Alfred Wegener in 1915. The evidence he presented for **continental drift** was based on the congruity of the shape of continents, particularly those across the Atlantic Ocean, and on the similarity in fossils found in South America and Africa. Wegener's hypothesis was not taken seriously because there was no known mechanism that could explain the movement of continents around Earth. The explanation came in the 1960s, when **seafloor spreading** was discovered. In seafloor regions called **mid-oceanic ridges**, or **spreading centers**, new crust is continuously added to the edges of lithospheric plates (Figure 2.5, left). As oceanic lithosphere is added along some plate edges (spreading centers), it is destroyed along other plate edges, such as at **subduction zones** (i.e., areas where one plate sinks beneath another and is destroyed) (see Figure 2.5, right). Thus, continents do not move *through* oceanic crust; rather, they are *carried along with it* by the movement of the plates. Also, because the rate of



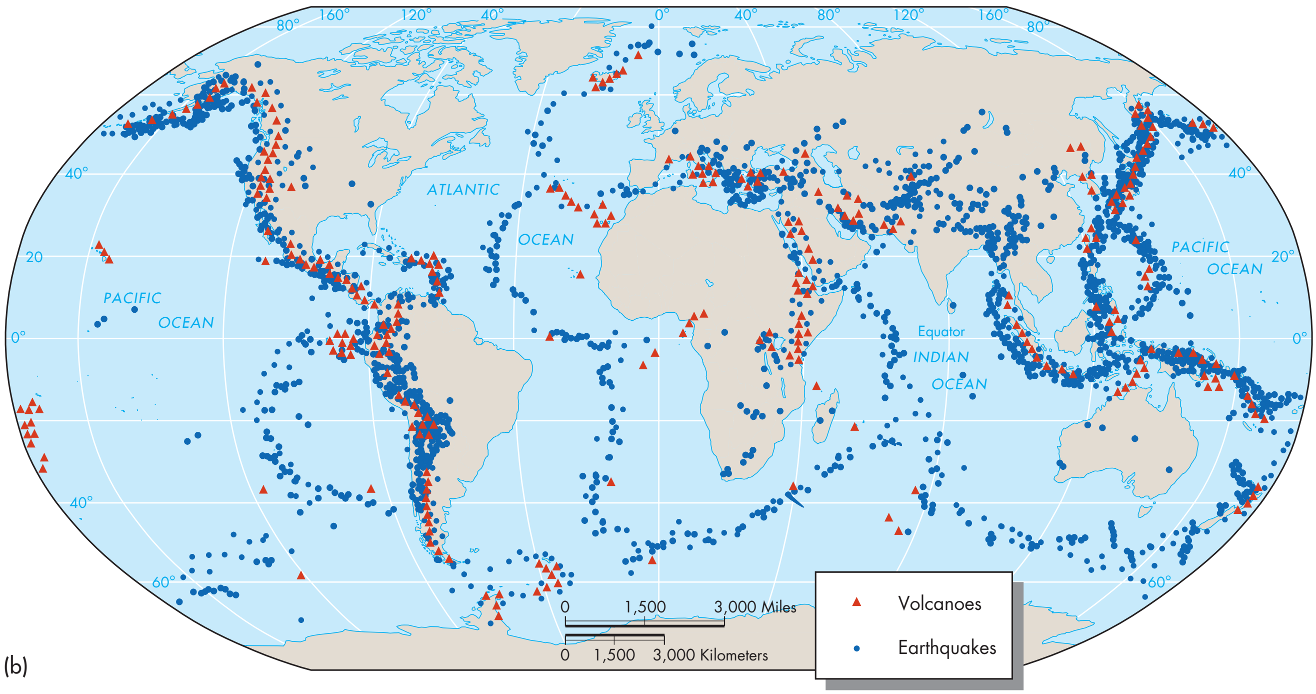
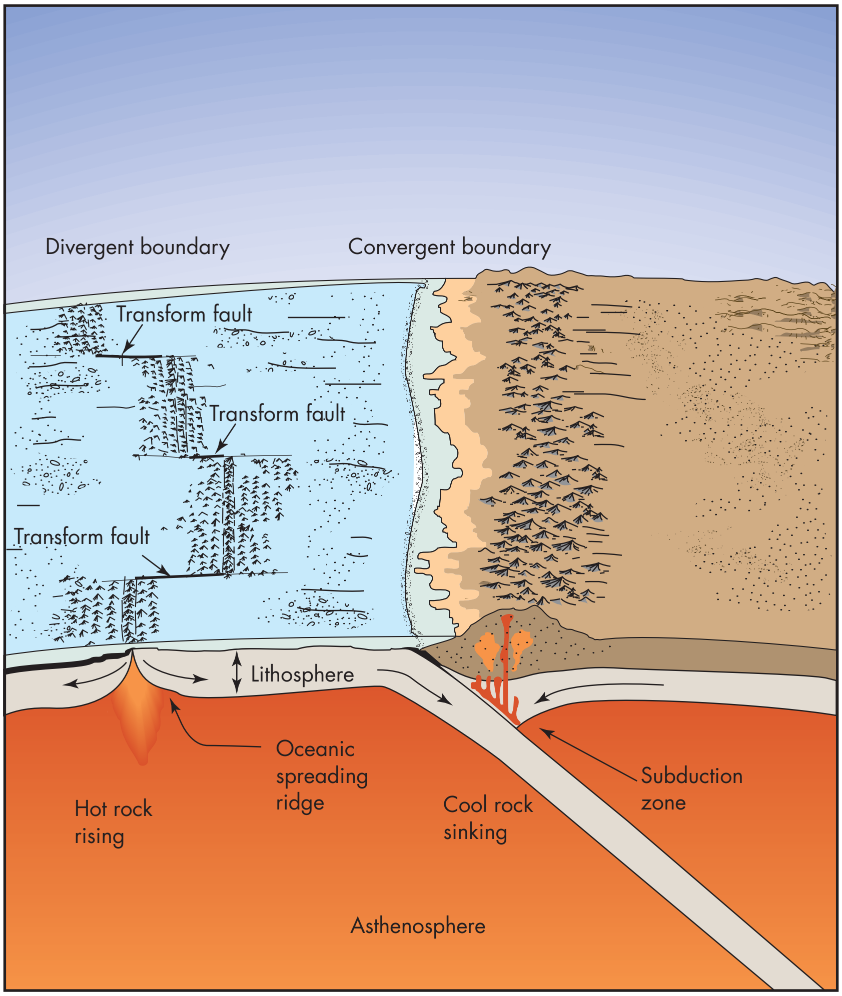


FIGURE 2.4 Earth's plates (a) Map showing the major tectonic plates, plate boundaries, and direction of plate movement. *(Modified from Christopherson, R. W. 1994.* Geosystems, *2nd ed. Englewood Cliffs, NJ: Macmillan)* (b) Volcanoes and earthquakes: Map showing location of volcanoes and earthquakes. Notice the correspondence between this map and the plate boundaries. *(Modified after Hamblin, W. K. 1992.* Earth's Dynamic Systems, *6th ed. New York: Macmillan)*

FIGURE 2.5 Model of plate tectonics Diagram of the model of plate tectonics. New oceanic lithosphere is being produced at the spreading ridge (i.e., divergent plate boundary). Elsewhere, oceanic lithosphere returns to the interior of Earth at a convergent plate boundary (subduction zone). *(Modified from Lutgens, F., and Tarbuck, E. 1992.* Essentials of Geology. *New York: Macmillan)*



production of new lithosphere at spreading centers is balanced by consumption at subduction zones, the size of Earth remains constant, neither growing nor shrinking.

Sinking Plates Generate Earthquakes. The concept of a lithospheric plate sinking into the upper mantle is shown in diagrammatic form in Figure 2.5. When the wet, cold oceanic crust comes into contact with the hot asthenosphere, magma is generated. The magma rises back to the surface, producing volcanoes, such as those that ring the Pacific Ocean basin, over subduction zones. The path of the descending plate (or *slab*, as it sometimes is called) into the upper mantle is clearly marked by earthquakes. As the oceanic plate subducts, earthquakes are produced both between it and the overriding plate and within the interior of the subducting plate. The earthquakes occur because the sinking

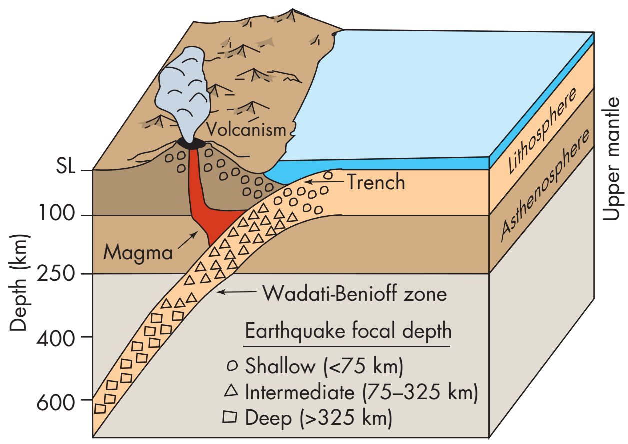


FIGURE 2.6 Subduction zone Idealized diagram of a subduction zone showing the Wadati-Benioff zone, which is an array of earthquake foci from shallow to deep that delineate the subduction zone and the descending lithospheric plate.

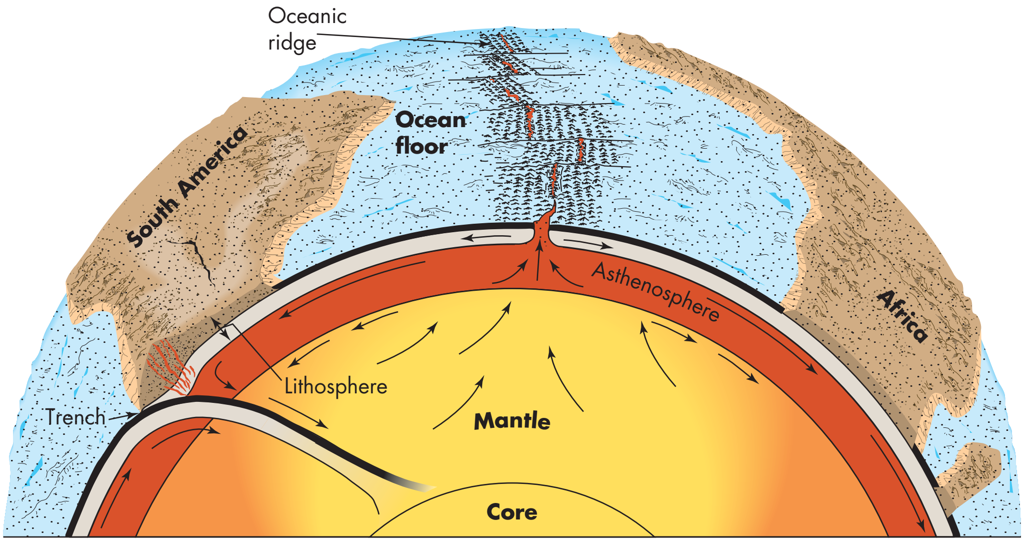


FIGURE 2.7 Plate movement Model of plate movement and mantle. The outer layer (or lithosphere) is approximately 100 km (approximately 62 mi) thick and is stronger and more rigid than the deeper asthenosphere, which is a hot and slowly flowing layer of relatively low-strength rock. The oceanic ridge is a spreading center where plates pull apart, drawing hot, buoyant material into the gap. After these plates cool and become dense, they descend at oceanic trenches (subduction zones), completing the convection system. This process of spreading produces ocean basins, and mountain ranges often form where plates converge at subduction zones. A schematic diagram of Earth's layers is shown in Figure 2.2b. *(Grand, S. P. 1994. Mantle shear structure beneath the Americas and surrounding oceans.* Journal of Geophysical Research *99:11591–11621. Modified after Hamblin, W. K. 1992.* Earth's Dynamic Systems, *6th ed. New York: Macmillan)*

lithospheric plate is relatively cooler and stronger than the surrounding asthenosphere; this difference causes rocks to break and seismic energy to be released.[6]

The paths of descending plates at subduction zones may vary from a shallow dip to nearly vertical, as traced by the earthquakes in the slabs. These dipping planes of earthquakes are called **Wadati-Benioff zones** (**Figure 2.6**). The very existence of Wadati-Benioff zones is strong evidence that subduction of rigid "breakable" lithosphere is occurring.[6]

Plate Tectonics Is a Unifying Theory. The theory of plate tectonics is to geology what Darwin's origin of species is to biology: a unifying concept that explains an enormous variety of phenomena. Biologists now have an understanding of evolutionary change. In geology, we are still seeking the exact mechanism that drives plate tectonics, but we think it is most likely convection within Earth's mantle. As rocks are heated deep in Earth, they become less dense and rise. Magma leaks out, cools to form rock and is added to the surfaces of plates at spreading centers. As the rocks move laterally, they cool, eventually becoming dense enough to sink back into the mantle at subduction zones. This circulation is known as convection, which was introduced in Section 2.1. **Figure 2.7** illustrates the cycles of convection that may drive plate tectonics.

Types of Plate Boundaries

There are three basic types of plate boundaries: divergent, convergent, and transform (see Figures 2.4 and 2.5 and **Table 2.1**). These boundaries are not narrow cracks, as shown on maps and diagrams; rather, they are zones that range from a few kilometers to hundreds of kilometers across. Plate boundary zones are narrower in ocean crust and broader in continental crust.

Divergent boundaries occur where new lithosphere is being produced and neighboring parts of plates are moving away from each other. Typically, this process occurs at mid-ocean ridges, and the process is called *seafloor spreading* (Figure 2.5). Mid-ocean ridges form when hot material from the

TABLE 2.1 Types of Plate Boundaries: Dynamics, Results, and Examples

Plate Boundary	Plates Involved	Dynamics	Results	Example
Divergent	Usually oceanic	Spreading. The two plates move away from one another, and molten rock rises up to fill the gap.	Mid-ocean ridge forms, and new material is added to each plate.	African and North American plate boundary (Figure 2.4a) Mid-Atlantic Ridge
Convergent	Ocean–continent	Oceanic plate sinks beneath continental plate.	Mountain ranges and a subduction zone are formed with a deep trench. Earthquakes and volcanic activity are found here.	Nazca and South American plate boundary (Figure 2.4a) Andes Mountains Peru-Chile Trench
Convergent	Ocean–ocean	Older, denser, oceanic plate sinks beneath the younger, less dense oceanic plate.	A subduction zone is formed with a deep trench. Earthquakes and volcanic activity are found here.	Fiji plate (Figure 2.4a) Fiji Islands
Convergent	Continent–continent	Neither plate is dense enough to sink into the asthenosphere; compression results.	A large, high mountain chain is formed, and earthquakes are common.	Indo-Australian and Eurasian plate boundary (on land) (Figure 2.4a) Himalaya Mountains
Transform	Ocean–ocean or continent–continent	The plates slide past one another.	Earthquakes are common. May result in some topography such as linear troughs and uplifts (often appearing as lines [faults] at nearly right angle to the ridge).	North American and Pacific plate boundary (Figures 2.10 and 2.21) San Andreas fault

mantle rises up to form a broad ridge, typically with a central rift valley. It is called a *rift valley*, or *rift*, because the plates moving apart are pulling the crust apart and splitting, or rifting, it. Molten volcanic rock that is erupted along this rift valley cools and forms new plate material. The system of mid-oceanic ridges along divergent plate boundaries forms linear submarine mountain chains that are found in virtually every ocean basin on Earth.

Convergent boundaries occur where plates collide. If one of the converging plates is oceanic and the other is continental, an oceanic–continental plate collision results. The higher-density oceanic plate descends, or subducts, into the mantle beneath the leading edge of the continental plate, producing a subduction zone (Figure 2.5). The convergence or collision of a continent with an ocean plate can result in compression. *Compression* is a type of stress, or force per unit area. When an oceanic–continental plate collision occurs, compression is exerted on the lithosphere, resulting in shortening of the surface of Earth, like pushing a table cloth to produce folds. Shortening can cause folding, as in the table cloth example, and faulting, or displacement of rocks along fractures to thicken the lithosphere (**Figure 2.8a**). This process of deformation produces major mountain chains and volcanoes such as the Andes in South America and

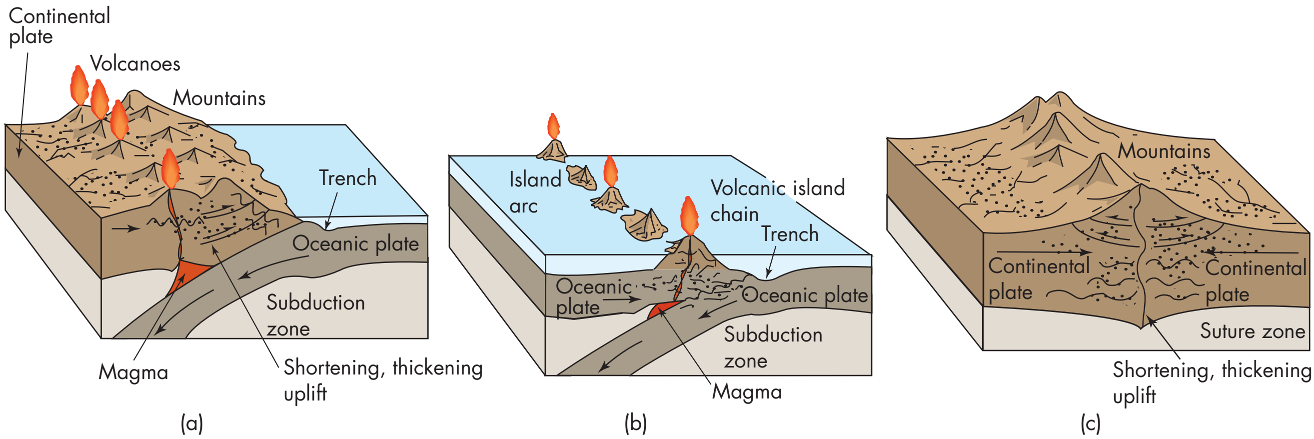


FIGURE 2.8 Convergent plate boundaries Idealized diagram illustrating characteristics of convergent plate boundaries: (a) continental–oceanic plate collision, (b) oceanic–oceanic plate collision, and (c) continental–continental plate collision.

the Cascade Mountains in the Pacific Northwest of the United States (see A Closer Look: The Wonder of Mountains). If two oceanic lithospheric plates collide (oceanic-to-oceanic plate collision), one plate subducts beneath the other, and a subduction zone and arc-shaped chain of volcanoes known as an *island arc* is formed (Figure 2.8b) as, for example, the Aleutian Islands of the North Pacific. A **submarine trench**, relatively narrow depression on the ocean floor (usually several thousand kilometers long and several kilometers deep), is often formed as the result of the convergence of two colliding plates, with the subduction of one. A trench is often located seaward of a subduction zone associated with an oceanic–continental plate or oceanic–oceanic plate collision. Submarine trenches are sites of some of the deepest oceanic waters on Earth. For example, the Marianas trench at the center edge of the Philippine plate is 11 km (7 mi) deep. Other major trenches include the Aleutian trench south of Alaska and the Peru–Chile trench west of South America. If the leading edges of both plates contain relatively light, buoyant continental crust, subduction into the mantle of one of the plates is difficult. In this case, a continent-to-continent plate collision occurs, in which the edges of the plates collide, causing shortening and lithospheric thickening due to folding and faulting. (Figure 2.8c). Where the two plates join is known as a *suture zone*. Continent-to-continent collision has produced some of the highest mountain systems on Earth, such as the Alpine and Himalayan mountain belts (Figure 2.9). Many older mountain belts were formed in a similar way; for example, the Appalachians formed during an ancient continent-to-continent plate collision 250 to 350 million years ago.

FIGURE 2.9 Mountains in Italy Mountain peaks (the Dolomites) in southern Italy are part of the Alpine mountain system formed from the collision between Africa and Europe. *(Edward A. Keller)*

Transform boundaries, or transform faults, occur where the edges of two plates slide past one another, as shown in Figure 2.5. If you examine Figures 2.4a and 2.5, you will see that a spreading zone is not a

A Closer Look

The Wonder of Mountains

Mountains have long fascinated people with their awesome presence. We are now discovering a fascinating story concerning their origin. The story removes some of the mystery as to how mountains form, but it has not removed the wonder. The new realization that mountains are systems (see Chapter 1) resulting from the interaction between tectonic activity (that leads to crustal thickening), the climate of the mountain, and Earth surface processes (particularly erosion) has greatly expanded our knowledge of how mountains develop.[7,8] Specifically, we have learned the following:

- Tectonic processes at convergent plate boundaries lead to crustal thickening and initial development of mountains. The mean (or average) elevation that a mountain range attains is a function of the uplift rate, which varies from less than 1 mm to about 10 mm per year (0.04 to 0.4 in. per year). The greater the rate of uplift, the higher the point to which the mean elevation of a mountain range is likely to rise during its evolution.
- As a mountain range develops and gains in elevation, it begins to modify the local and regional climate by blocking storm paths and producing a "rain shadow" in which the mountain slopes on the rain shadow side receive much less rainfall than does the other side of the mountain. As a result, rates of runoff and erosion on the side of the rain shadow are less than for the other side. Nevertheless, the rate of erosion increases as the elevation of the mountain range increases, and eventually the rate of erosion matches the rate of uplift. When the two match, the mountain reaches its maximum mean elevation, which is a dynamic balance between uplift and erosion. At this point, no amount of additional uplift will increase the mean elevation of the mountains above the dynamic maximum. However, if the uplift rate increases, then a higher equilibrium mean elevation of the range may be reached. Furthermore, when the uplift ceases or there is a reduction in the rate of uplift, the mean elevation of the mountain range will decrease.[7] Strangely, the elevations of individual peaks may still increase!
- Despite erosion, the elevation of a mountain peak in a range may actually increase. This statement seems counterintuitive until we examine in detail some of the physical processes resulting from erosion. The uplift that results from the erosion is known as isostatic uplift. **Isostasy** is the principle whereby thicker, more buoyant crust stands topographically higher than crust that is thinner and denser. The principle governing how erosion can result in uplift is illustrated in Figure 2.A. The fictitious Admiral Frost has been marooned on an iceberg and is uncomfortable being far above the surface of the water. He attempts to remove the ice that is above the water line. Were it not for isostatic (buoyant) uplift, he would have reached his goal to be close to the water line. Unfortunately for Admiral Frost, this is not the way the world works; continuous isostatic uplift of the block as ice is removed always keeps one-tenth of the iceberg above the water. So, after removing the ice above the water line, he still stands almost as much above the water line as before.[7]
- Mountains, of course, are not icebergs, but the rocks of which they are composed are less dense than the rocks of the mantle beneath. Thus, they tend to "float" on top of the denser mantle. Also, in mountains, erosion is not uniform but is generally confined to valley walls and bottoms. Thus, as erosion continues and the mass of the mountain range is reduced, isostatic compensation occurs, and the entire mountain range rises in response. As a result of the erosion, the maximum elevation of mountain peaks actually may increase, while the mean elevation of the entire mountain block decreases. As a general rule, as the equivalent of 1 km (0.6 mi) of erosion across the entire mountain block occurs, the mean elevation of mountains will rise approximately 0.83 km (0.5 mi).

In summary, research concerning the origin of mountains suggests that they result in part from tectonic processes that cause the uplift, but they also are intimately related to climatic and erosional processes that contribute to the mountain building process. Erosion occurs during and after tectonic uplift, and isostatic compensation to that erosion occurs for millions of years. This is

one reason it is difficult to remove mountain systems from the landscape. For example, mountain systems such as the Appalachian Mountains in the southeastern United States were originally produced by tectonic uplift several hundred million years ago, when Europe collided with North America. There has been sufficient erosion of the original Appalachian Mountains to have removed them as topographic features many times over were it not for continued isostatic uplift in response to the erosion.

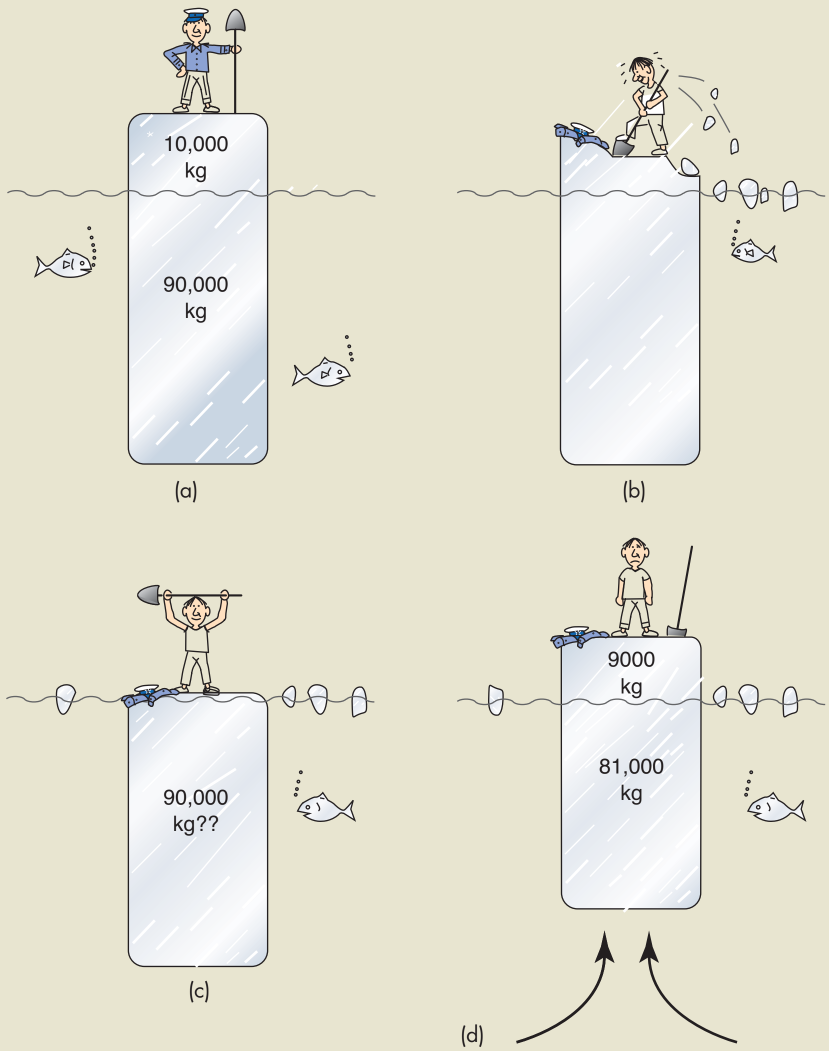


FIGURE 2.A Isostasy Cartoon showing the principle of isostatic uplift. Admiral Frost is left adrift on an iceberg and is uncomfortable being so far above the surface of the water (a). He decides to remove the 10,000 kg (22,046 lb) of ice that is above the water line on the iceberg on which he is standing (b). Were it not for isostatic (buoyant) uplift, Admiral Frost would reach his goal (c). However, in a world with isostasy, uplift results from removal of the ice, and one-tenth of the iceberg is always above the water (d). What would have happened if Admiral Frost had elected to remove 10,000 kg of ice from only one-half of the area of ice exposed above the sea? Answer: The maximum elevation of the iceberg above the water would have actually increased. Similarly, as mountains erode, isostatic adjustments also occur, and the maximum elevation of mountain peaks may actually increase as a result of the erosion alone! *(From Keller, E. A., and Pinter, N. 1996.* Active Tectonics. *Upper Saddle River, NJ: Prentice Hall)*

single, continuous rift but a series of rifts that are offset from one another along connecting transform faults. Although the most common locations for transform plate boundaries are within oceanic crust, some occur within continents. A well-known continental transform boundary is the San Andreas fault in California, where the rim of the Pacific plate is sliding horizontally past the rim of the North American plate (see Figures 2.4a and 2.10).

Locations where three plates border one another are known as **triple junctions**. Figure 2.10 shows several such junctions: Two examples are the meeting point of the Juan de Fuca, North American, and Pacific plates on the West Coast of North America (this is known as the Mendocino triple junction) and the junction of the spreading ridges associated with the Pacific, Cocos, and Nazca plates west of South America.

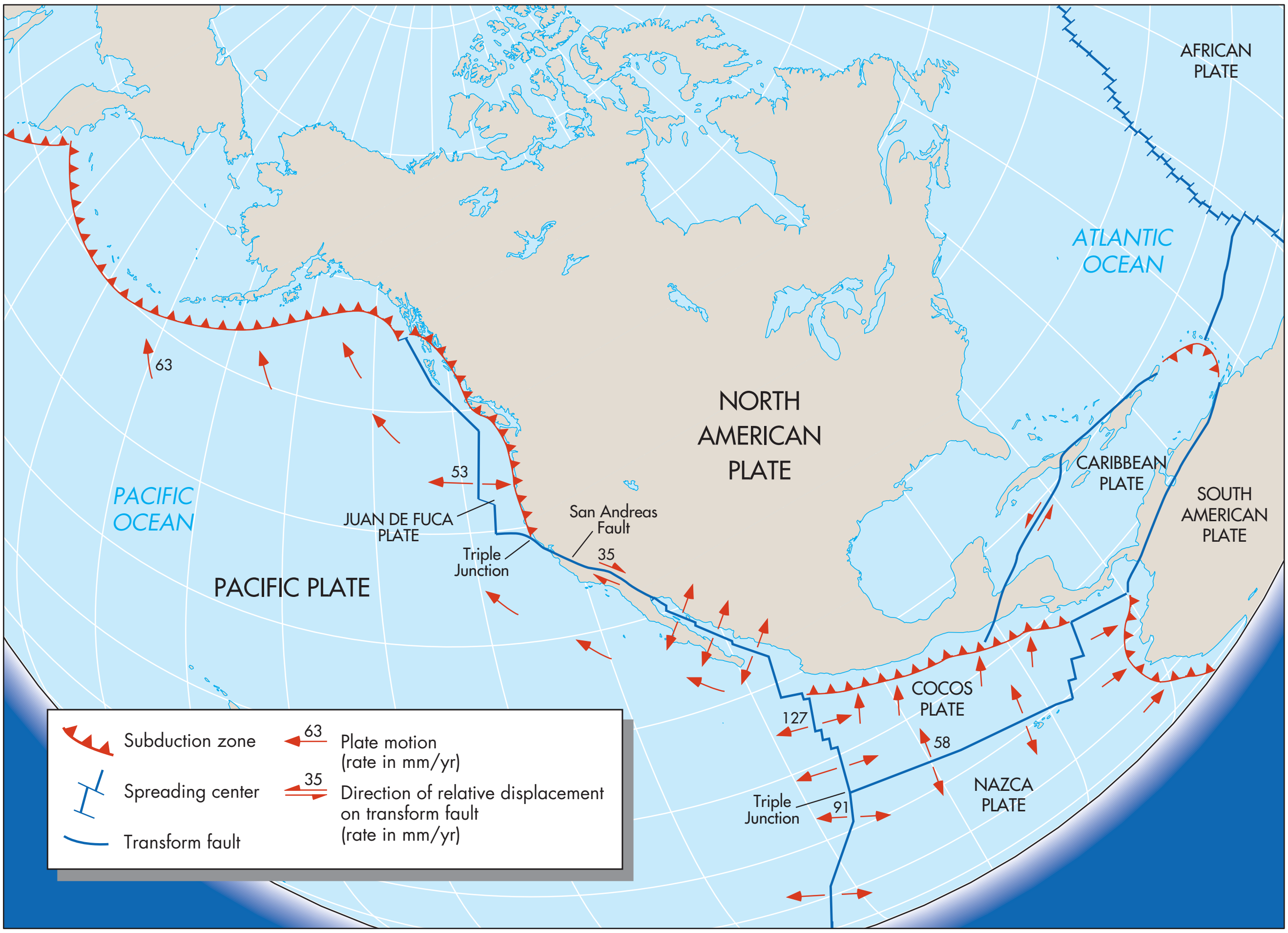


FIGURE 2.10 North American plate boundary Detail of boundary between the North American and Pacific plates. *(Courtesy of Tanya Atwater)*

Rates of Plate Motion

Plate Motion Is a Fast Geologic Process. The directions in which plates move are shown in Figure 2.4a. In general, plates move a few centimeters per year, about as fast as some people's fingernails or hair grows. The Pacific plate moves past the North American plate along the San Andreas fault about 3.5 cm (1.4 in.) per year, so that features such as rock units or streams are gradually displaced over time where they cross the fault (**Figure 2.11**). During the past 5 million years, there has been about 175 km (about 110 mi) of displacement, a distance equivalent to driving 2 hours at 55 mph on a highway along the San Andreas fault. Although the central portions of the plates move along at a steady slow rate, plates interact at their boundaries, where collision or subduction or both occur, and movement may not be smooth or steady. The plates often get stuck together. The movement is analogous to sliding one rough wood board over another. Movement occurs when the splinters of the boards break off and the boards move quickly by one another. When rough edges along the plate move quickly, an earthquake is produced. Along the San Andreas fault, which is a transform plate boundary, the displacement is horizontal and can amount to several meters during a great earthquake. During an earthquake in 1857 on the San Andreas fault, a horse corral across the fault was reportedly changed from a circle to an "S" shape. Fortunately, such an event generally occurs at any given location only

FIGURE 2.11 The San Andreas fault The fault is visible from the lower left to upper right diagonally across the photograph, as if a gigantic plow had been dragged across the landscape. *(James Balog)*

once every 100 years or so. Over long time periods, rapid displacement from periodic earthquakes and more continuous slow "creeping" displacements add together to produce the rate of several centimeters of movement per year along the San Andreas fault.

2.4 A Detailed Look at Seafloor Spreading

When Alfred Wegener proposed the idea of continental drift in 1915, he had no solid evidence of a mechanism that could move continents. The global extent of mid-oceanic ridges was discovered in the 1950s, and in 1962 geologist Harry H. Hess published a paper suggesting that continental drift was the result of the process of seafloor spreading along those ridges. The fundamentals of seafloor spreading are shown in Figure 2.5. New oceanic lithosphere is produced at the spreading ridge (i.e., divergent plate boundary). The lithospheric plate then moves laterally, carrying along the embedded continents in the tops of moving plates. These ideas produced a new major paradigm that greatly changed our ideas about how Earth works.[3,6,9]

The validity of seafloor spreading was established from three sources: (1) identification and mapping of oceanic ridges, (2) dating of volcanic rocks on the floor of the ocean, and (3) understanding and mapping of the paleomagnetic history of ocean basins.

Paleomagnetism

We introduce and discuss Earth's magnetic field and paleomagnetic history in some detail in order to understand how seafloor spreading and plate tectonics were discovered. Earth has had a magnetic field for at least the past 3.5 billion years (**Figure 2.12a**).[2] The field can be represented by a dipole magnetic field with lines of magnetic force extending from the South Pole to the North Pole. A dipole magnetic field is one that has equal and opposite charges at either end. Convection occurs in the iron-rich, fluid, hot outer core of Earth because of compositional changes and heat at the inner-outer core boundary. As more buoyant material in the outer core rises, it starts the convection (Figures 2.3 and 2.7). The convection in the outer core, along with the rotation of Earth that causes rotation of the outer core, initiates a flow of electric current in the core. This flow of current within the core produces and sustains Earth's magnetic field.[2,3]

Earth's magnetic field is sufficient to permanently magnetize some surface rocks. For example, volcanic rock that erupts and cools at mid-oceanic

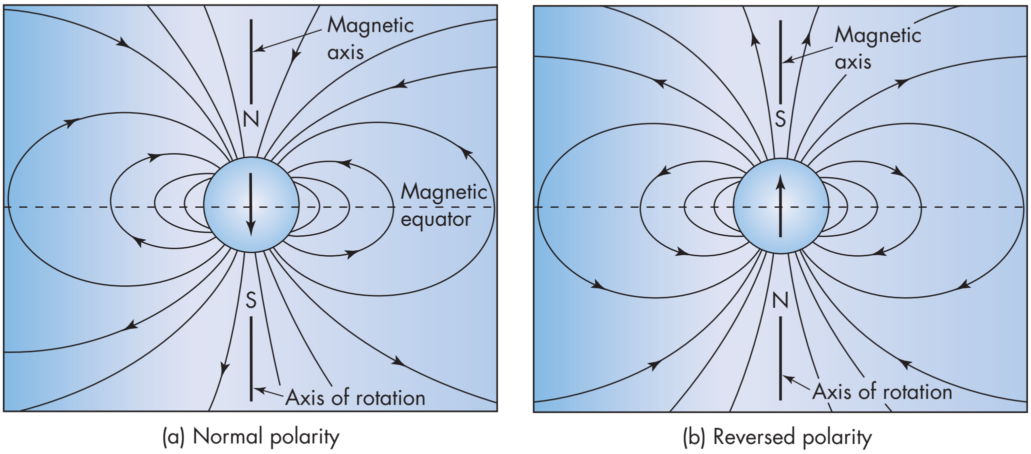


FIGURE 2.12 Magnetic reversal Idealized diagram showing the magnetic field of Earth under (a) normal polarity and (b) reversed polarity. *(From Kennett, J. 1982.* Marine Geology. *Englewood Cliffs, NJ: Prentice Hall)*

ridges becomes magnetized at the time it passes through a critical temperature. At that critical temperature, known as the *Curie point*, magnetic domains within iron-bearing minerals (such as magnetite) in the volcanic rock orient themselves parallel to the magnetic field. This is a permanent magnetization known as *thermoremnant magnetization*.[3] The term **paleomagnetism** refers to the study of the magnetism of rocks at the time their magnetic signature formed. It is used to determine the magnetic history of Earth.

The magnetic field, based on the size and conductivity of Earth's core, must be continuously generated or it would decay away in about 20,000 years. It would decay because the temperature of the core is too high to sustain permanent magnetization.[2]

Earth's Magnetic Field Periodically Reverses. Before the discovery of plate tectonics, geologists working on land had already discovered that some volcanic rocks were magnetized in a direction opposite to the present-day field, suggesting that the polarity of Earth's magnetic field was reversed at the time the volcanoes erupted and the rocks cooled (Figure 2.12b). The rocks were examined for whether their magnetic field was normal, as it is today, or reversed relative to that of today, for certain time intervals of the Earth's history. A chronology for the past few million years was constructed on the basis of the dating of the "reversed" rocks. You can verify the current magnetic field of the Earth by using a compass; at this point in Earth's history, the needle points to the north magnetic pole. During a period of reversed polarity, the needle would point south! The cause of **magnetic reversals** is not well known, but it is related to changes in the convective movement of the liquid material in the outer core and processes occurring in the inner core. Reversals in Earth's magnetic field are apparently random, occurring on average every few hundred thousand years. The change in polarity of Earth's magnetic field takes a few thousand years to occur, which in geologic terms is a very short time.

What Produces Magnetic Stripes? To further explore the Earth's magnetic field, geologists towed magnetometers, instruments that measure magnetic properties of rocks, from ships and completed magnetic surveys. The paleomagnetic record of the ocean floor is easy to read because of the fortuitous occurrence of the volcanic rock basalt (see Chapter 3) that is produced at spreading centers and forms the floors of the ocean basins of Earth. The rock is fine grained and contains sufficient iron-bearing minerals to produce a good magnetic record. The marine geologists' discoveries were not expected. The rocks on the floor of the ocean were found to have irregularities in the magnetic field. These irregular magnetic patterns were called *anomalies* or *perturbations* of Earth's magnetic field caused by local fields of magnetized rocks on the seafloor. The

anomalies can be represented as stripes on maps. When mapped, the stripes form quasi-linear patterns parallel to oceanic ridges. The marine geologists found that their sequences of stripe width patterns matched the sequences established by land geologists for polarity reversals in land volcanic rocks. Magnetic survey data for an area southwest of Iceland are shown in **Figure 2.13**. The black stripes represent normally magnetized rocks, and the intervening white stripes represent reversed magnetized rocks.[10] Notice that the stripes are not evenly spaced but have patterns that are symmetrical on opposite sides of the Mid-Atlantic Ridge (Figure 2.13).

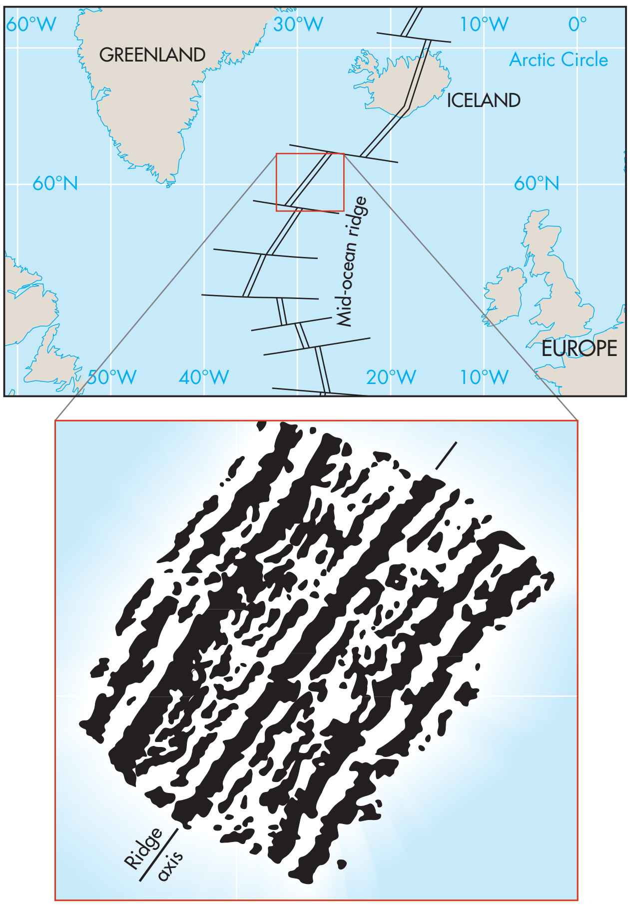


FIGURE 2.13 Magnetic anomalies on the seafloor
Map showing a magnetic survey southwest of Iceland along the Mid-Atlantic Ridge. Positive magnetic anomalies are black (normal) and negative magnetic anomalies are white (reversed). Note that the pattern is symmetrical on the two sides of the mid-oceanic ridge. *(From Heirtzler, J. R., Le Pichon, X., and Baron, J. G. 1966. Magnetic anomalies over the Reykjanes Ridge.* Deep-Sea Research *13:427–443)*

Why Is the Seafloor No Older Than 200 Million Years? The discovery of patterns of magnetic stripes at various locations in ocean basins allowed geologists to infer numerical dates for the volcanic rocks. Merging the magnetic anomalies with the numerical ages of the rocks produced the record of seafloor spreading. The spreading of the ocean floor, beginning at a mid-oceanic ridge, could explain the magnetic stripe patterns.[11] **Figure 2.14** is an idealized diagram showing how seafloor spreading may produce the patterns of magnetic anomalies (stripes). The pattern shown is for the past several million years, which includes several periods of normal and reversed magnetization of the volcanic rocks. Black stripes represent normally magnetized rocks, and brown stripes are rocks with a reversed magnetic signature. Notice that the most recent magnetic reversal occurred approximately 0.7 million years ago. The basic idea illustrated by Figure 2.14 is that rising magma at the oceanic ridge is extruded, or pushed out onto the surface, through volcanic activity, and the cooling rocks become normally magnetized. When the field is reversed, the cooling rocks preserve a reverse magnetic signature, and a brown stripe (Figure 2.14) is preserved. Notice that the patterns of magnetic anomalies in rocks on both sides of the ridge are mirror images of one another. The only way such a pattern might result is through the process of seafloor spreading. Thus, the pattern of magnetic reversals found on rocks of the ocean floor is strong evidence that the process of spreading is happening. Mapping of magnetic anomalies, when combined with age-dating of the magnetic reversals in land rocks, creates a database that suggests exciting inferences; **Figure 2.15** shows the age of the ocean floor as determined from this database. The pattern, showing that the youngest volcanic rocks are found along active mid-oceanic ridges, is consistent with the theory of seafloor spreading. As distance from these ridges increases, the age of the ocean floor also increases, to a maximum of about 200 million years, during the early Jurassic period (see Table 1.1). Thus, it appears that the present ocean floors of the world are no older than 200 million years. In contrast, rocks on continents are often much older than Jurassic, going back about 4 billion years, almost 20 times older than the ocean floors! We conclude that the thick continental crust, by virtue of its buoyancy, is more stable at Earth's

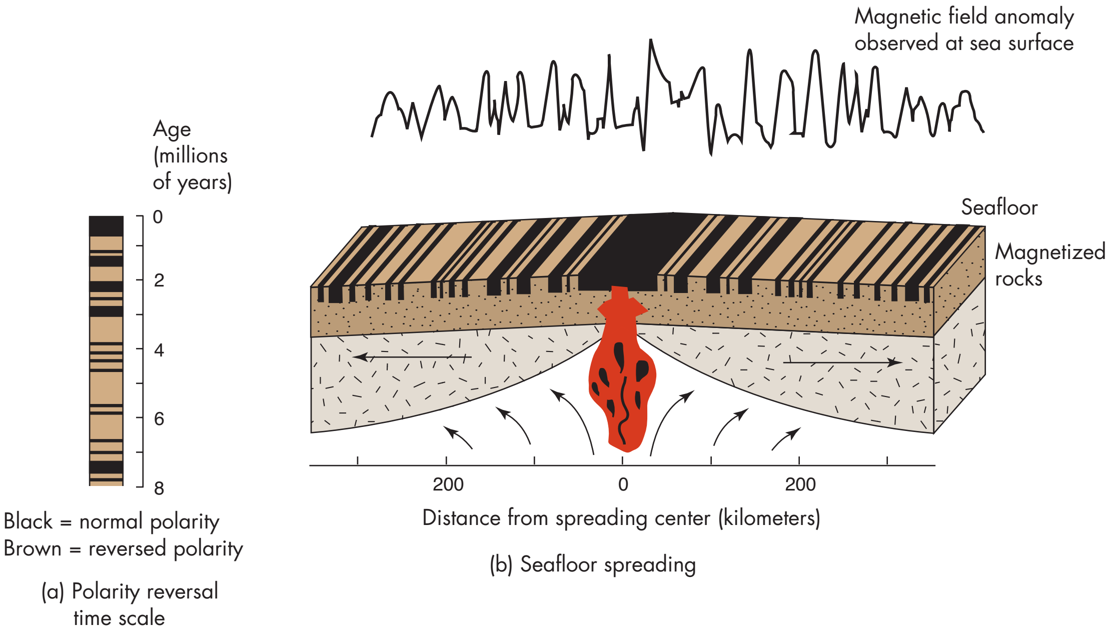


FIGURE 2.14 Magnetic reversals and seafloor spreading Idealized diagram showing an oceanic ridge and the rising of magma, in response to seafloor spreading. As the volcanic rocks cool, they become magnetized. The black stripes represent normal magnetization; the brown stripes are reversed magnetization. The record shown here was formed over a period of several million years. Magnetic anomalies (stripes) are a mirror image of each other on opposite sides of the mid-oceanic ridge. Thus, the symmetrical bands of the normally and reversely magnetized rocks are produced by the combined effects of the reversals and seafloor spreading. *(Courtesy of Tanya Atwater)*

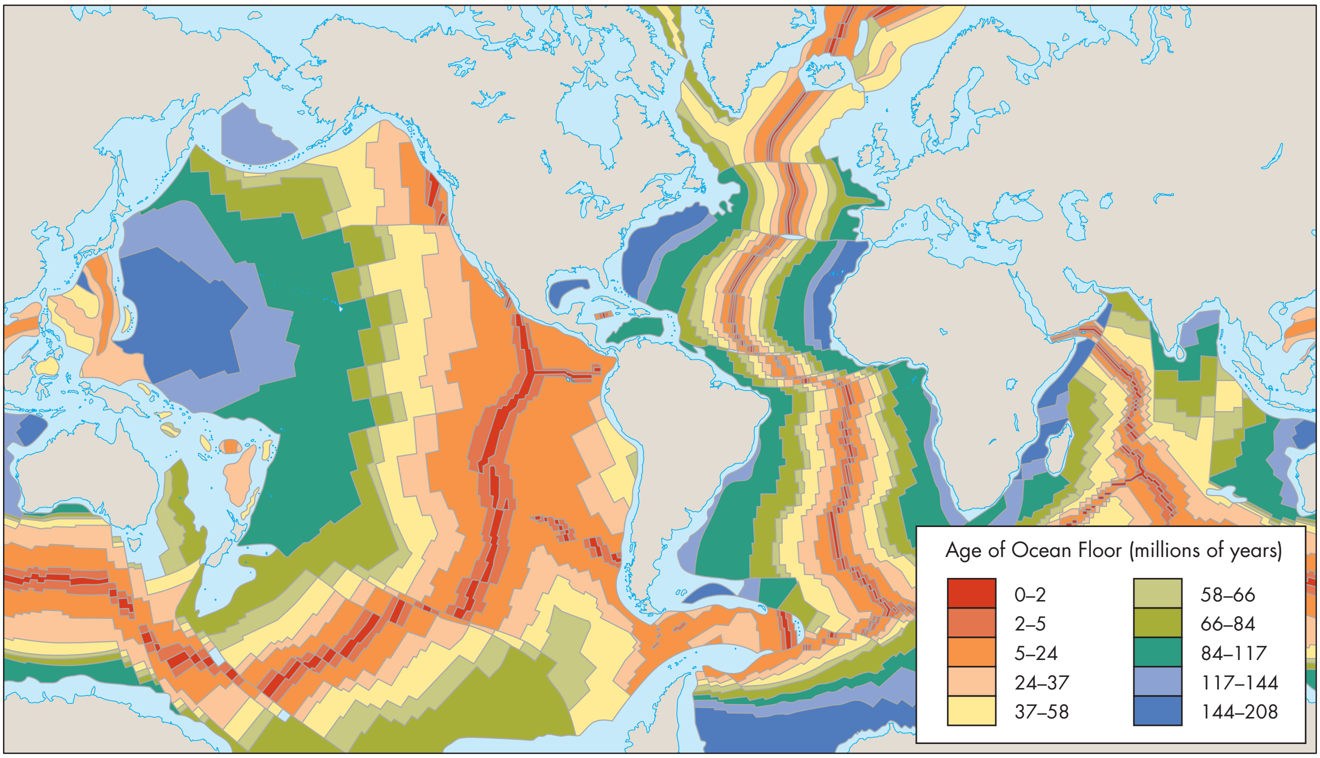


FIGURE 2.15 Age of the ocean floor Age of the seafloor is determined from magnetic anomalies and other methods. The youngest ocean floor (red) is located along oceanic ridge systems, and older rocks are generally farther away from the ridges. The oldest ocean floor rocks are approximately 180 million years old. *(From Scotese, C. R., Gahagan, L. M., and Larson, R. L. 1988. Plate tectonic reconstruction of the Cretaceous and Cenozoic ocean basins.* Tectonophysics *155:27–48)*

surface than are rocks of the crust of the ocean basins. Continents form by the processes of accretion of sediments, addition of volcanic materials, and collisions of tectonic plates carrying continental landmasses. We will continue this discussion when we consider the movement of continents during the past 200 million years. However, it is important to recognize that it is the pattern of magnetic stripes that allows us to reconstruct how the plates and the continents embedded in them have moved throughout history.

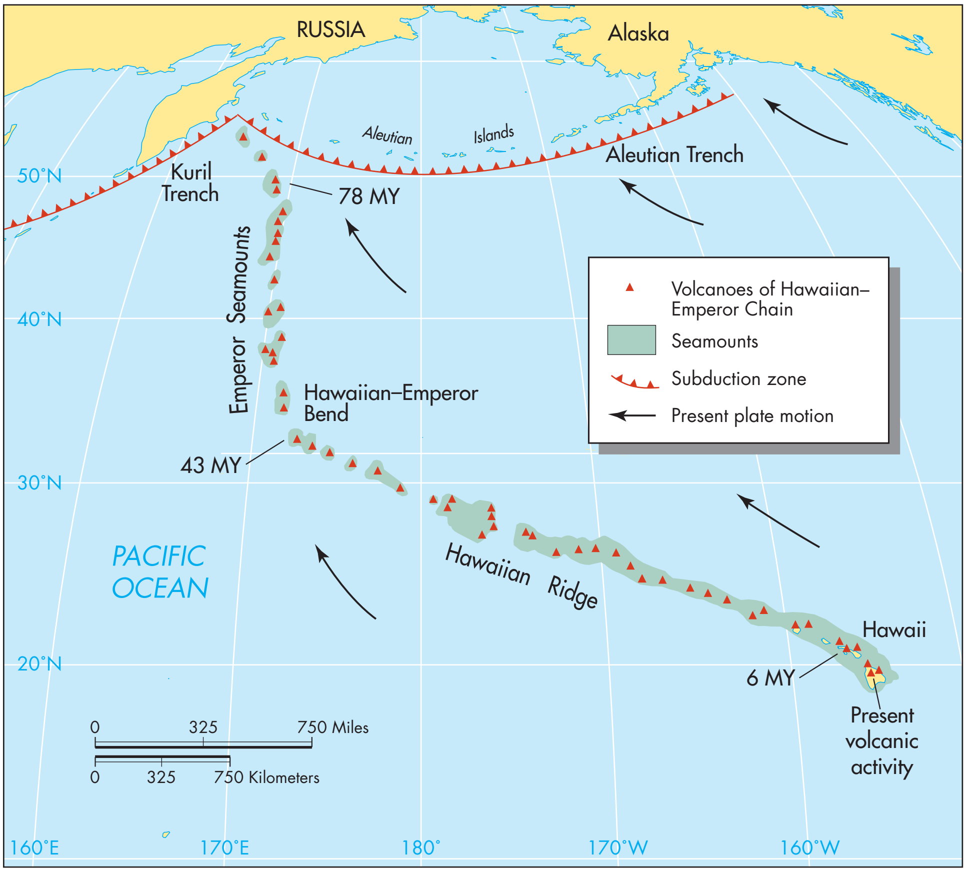
Hot Spots

What Are Hot Spots? There are a number of places on Earth called **hot spots**, characterized by volcanic centers resulting from hot rocks produced deep in the mantle, perhaps near the core–mantle boundary. The partly molten rock (magma) is buoyant enough to move up through mantle and overlying moving tectonic plates.[3,6] An example of a continental hot spot is the volcanic region of Yellowstone National Park. Hot spots are also found in both the Atlantic and Pacific Oceans. If the hot spot is anchored in the slow-moving deep mantle, then, as the plate moves over a hot spot, a chain of volcanoes is produced. Perhaps the best example of this type of hot spot is the line of volcanoes forming the Hawaiian–Emperor Chain in the Pacific Ocean (**Figure 2.16a**). Along this chain, volcanic eruptions range in age from present-day activity on the big island of Hawaii (in the southeast) to more than 78 million years ago near the northern end of the Emperor Chain. With the exception of the Hawaiian Islands and some coral atolls (i.e., ring-like coral islands such as Midway Island), the chain consists of submarine volcanoes known as *seamounts*. Seamounts are islands that were eroded by waves and submarine landslides and subsequently sank beneath the ocean surface. As seamounts move farther off the hot spot, the volcanic rocks the islands are composed of cool, and the oceanic crust they are on becomes denser and sinks.

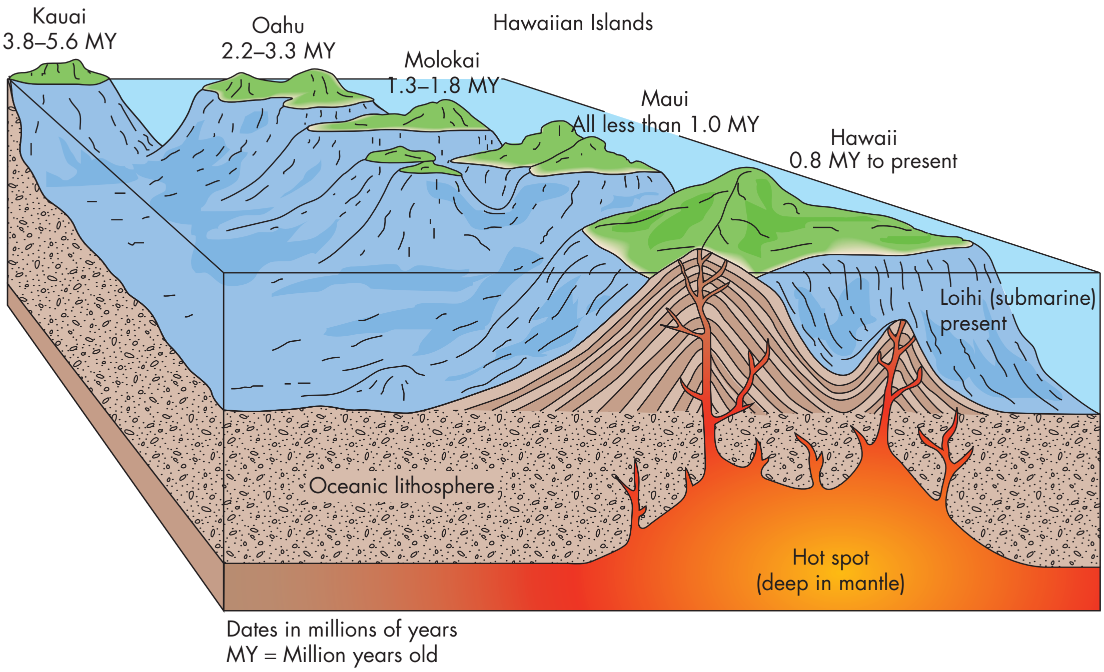
Seamounts constitute impressive submarine volcanic mountains. In the Hawaiian Chain, the youngest volcano is Mount Loihi, which is still a submarine volcano, presumably directly over a hot spot, as idealized in Figure 2.16b. The ages of the Hawaiian Islands increase to the northwest, with the oldest being Kauai, about 6 million years old. Notice in Figure 2.16a that the line of seamounts makes a sharp bend at the junction of the Hawaiian and Emperor Chains. The age of the volcanic rocks at the bend is about 43 million years, and the bend is interpreted to represent a time when plate motions changed.[12] If we assume that the hot spots are fixed deep in the mantle, then the chains of volcanic islands and submarine volcanoes along the floor of the Pacific Ocean that get older farther away from the hot spot provide additional evidence to support the theory of movement of the Pacific plate. In other words, the ages of the volcanic islands and submarine volcanoes could systematically change as they do only if the plate is moving over the hot spot.

2.5 Pangaea and Present Continents

Plate Tectonics Shapes Continents and Dictates the Location of Mountain Ranges. Movement of the lithospheric plates is responsible for the present shapes and locations of the continents. There is good evidence that the most recent global period of continental drift, driven by seafloor spreading, started about 200 million years ago, with the breakup of a supercontinent called Pangaea (this name, meaning "all lands," was first proposed by Wegener). Pangaea (pronounced pan-jee-ah) was enormous, extending from pole to pole and over halfway around Earth near the equator (**Figure 2.17**, page 61). Pangaea had two parts (Laurasia to the north and Gondwana to the south) and was constructed during earlier continental collisions. Figure 2.17a shows Pangaea as it was nearly 200 million years ago. Seafloor spreading over the past 200 million years separated Eurasia and North America from the southern landmass, Eurasia from North America, and the southern continents (South America, Africa, India, Antarctica, and Australia) from one another (Figure 2.17b–d). The Tethys Sea, between Africa and Europe-Asia (Figure 2.17a–c), closed, as part of the activity that produced the Alps in Europe. A small part of this once much larger sea remains today as the Mediterranean Sea (Figure 2.17d). About 50 million years ago, India crashed into China. That collision, which has caused India to forcefully intrude into China a distance comparable from New York to Miami, is still



(a)



(b)

FIGURE 2.16 Hawaiian hot spot (a) Map showing the Hawaiian–Emperor Chain of volcanic islands and seamounts. Actually, the only islands are Midway Island and the Hawaiian Islands at the end of the chain, where present volcanic activity is occurring. *(Modified after Claque, D. A., Dalrymple, G. B., and Moberly, R. 1975. Petrography and K-Ar ages of dredged volcanic rocks from the western Hawaiian Ridge and southern Emperor Seamount chain.* Geological Society of America Bulletin *86:991–998)* (b) Sketch map showing the Hawaiian Islands, which range in age from present volcanic activity to about 6 million years old on the island of Kauai. *(From Thurman,* Oceanography, *5th ed. Columbus, OH: Merrill, plate 2)*

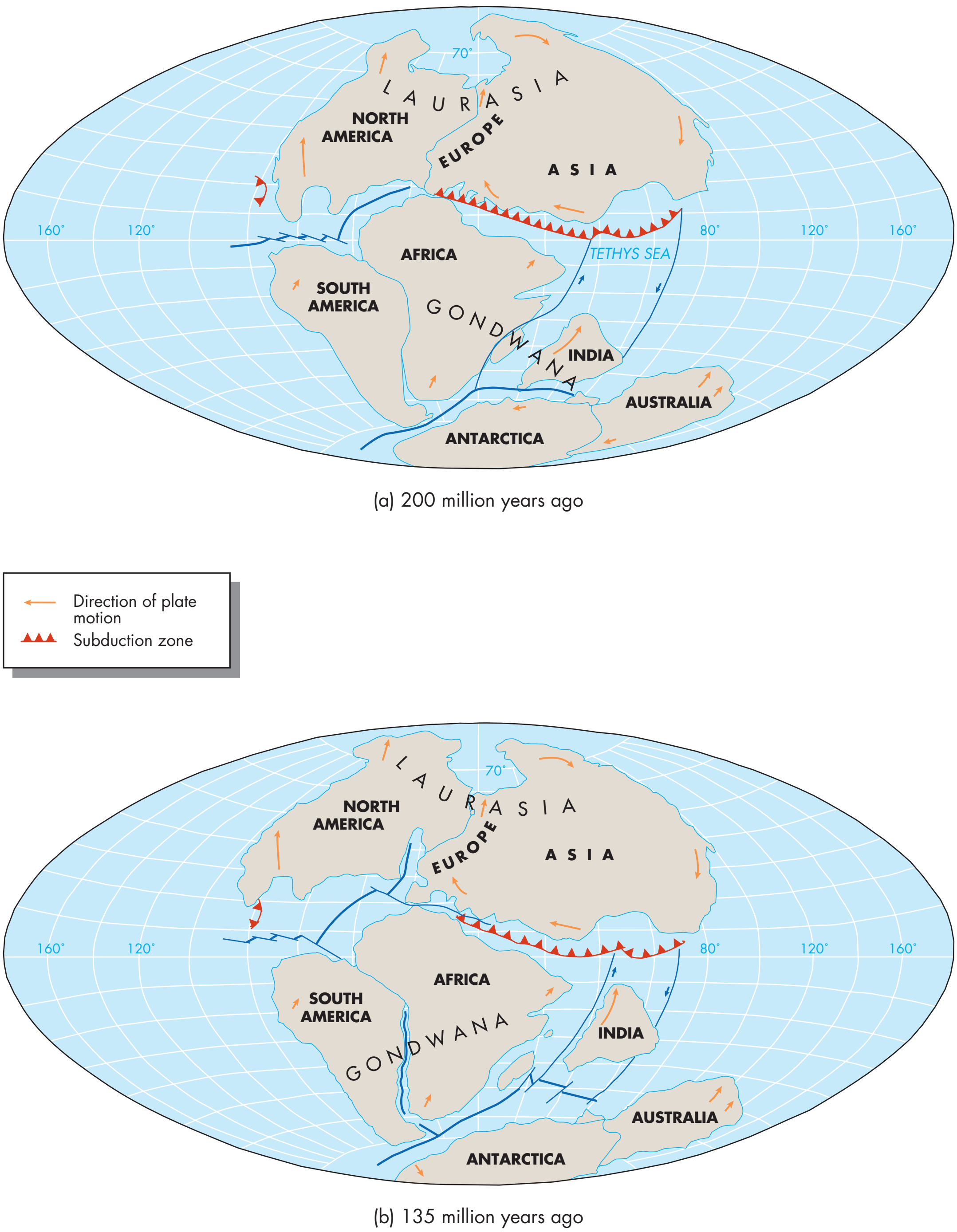
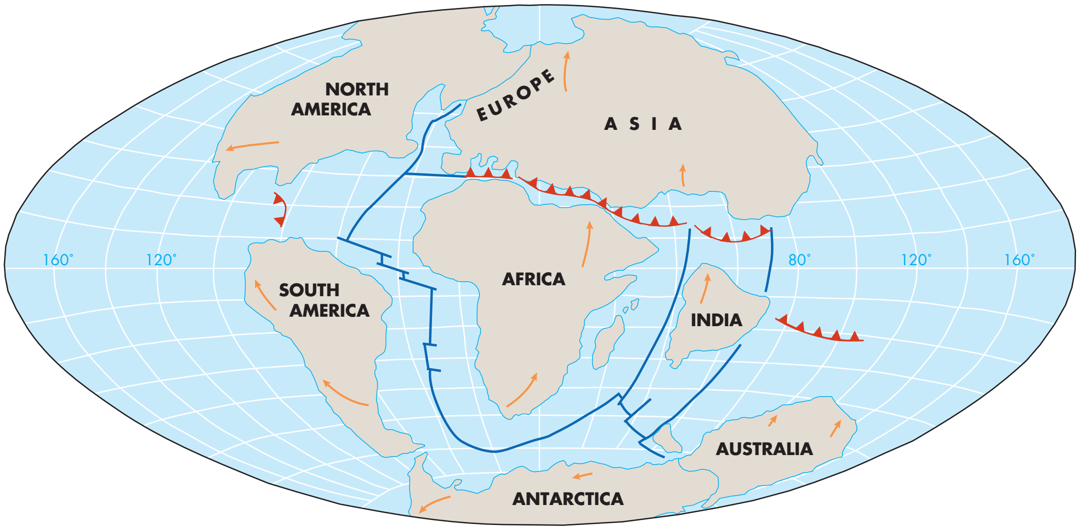
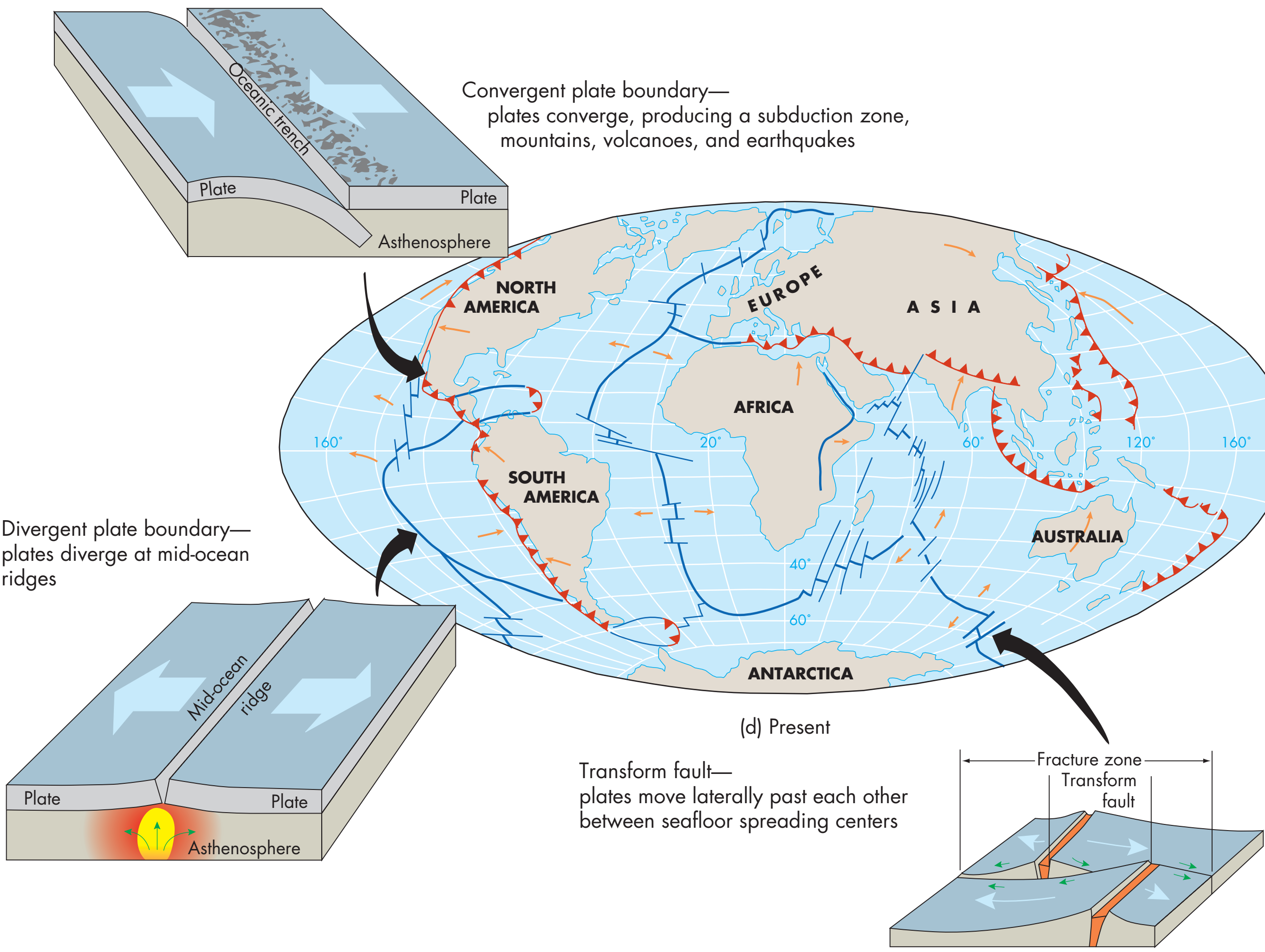


FIGURE 2.17 Two hundred million years of plate tectonics (a) The proposed positions of the continents at 200 million years ago; (b) 135 million years ago; (c) 65 million years ago; and (d) at present. Arrows show directions of plate motion. See text for further explanation of the closing of the Tethys Sea, the collision of India with China, and the formation of mountain ranges. *(From Dietz, R. S., and Holden, J. C. 1970. Reconstruction of Pangaea: breakup and dispersion of continents, Permian to present.* Journal of Geophysical Research *75(26):4939–4956. Copyright by the American Geophysical Union. Modifications and block diagrams from Christopherson, R. W. 1994.* Geosystems, *2nd ed. Englewood Cliffs, NJ: Macmillan)*



(c) 65 million years ago



(d) Present

FIGURE 2.17 ***(continued)***

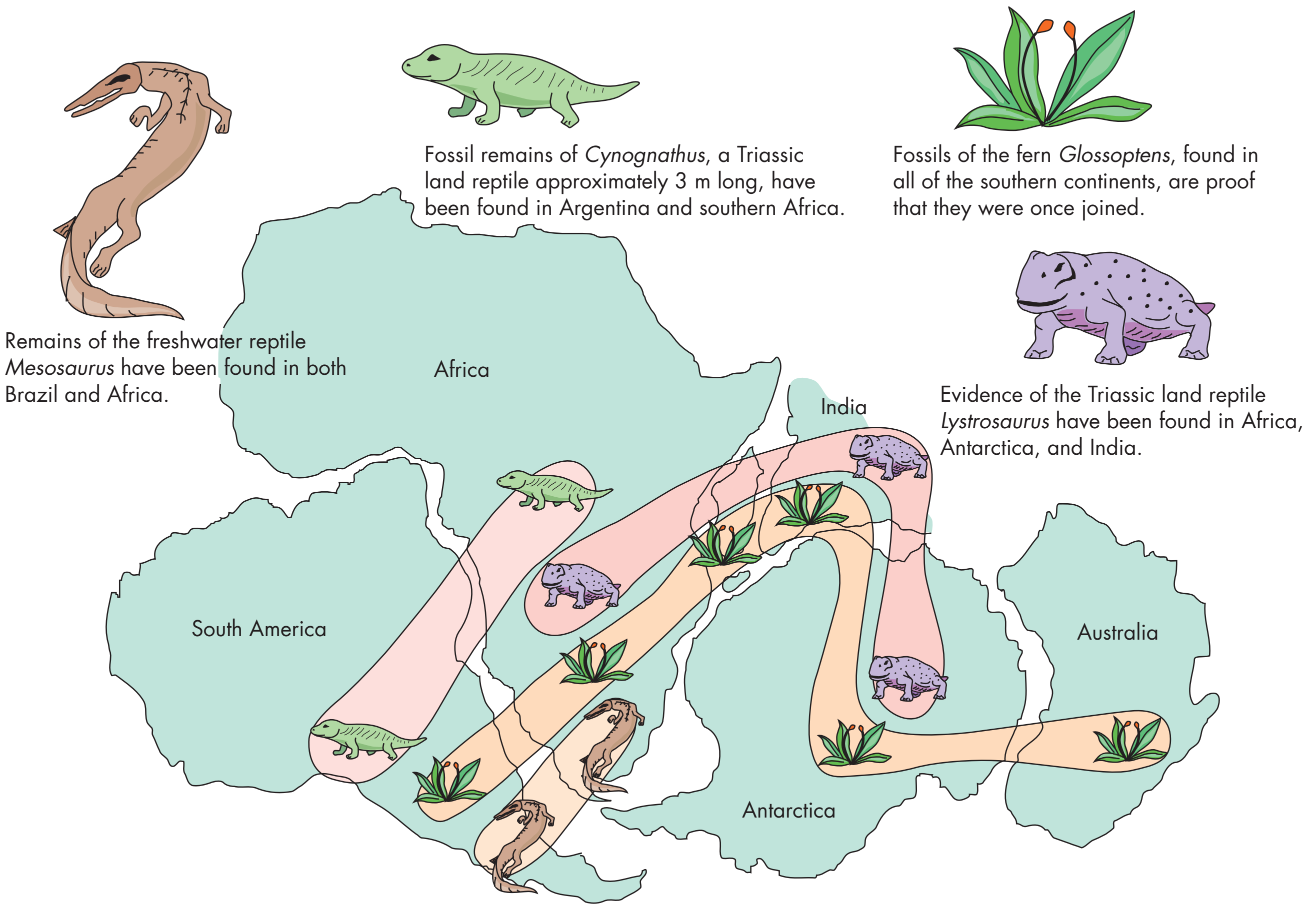


FIGURE 2.18 Paleontological evidence for plate tectonics This map shows some of the paleontological (fossil) evidence that supports continental drift. It is believed that these animals and plants could not have been found on all of these continents were they not once much closer together than they are today. Major ocean basins would have been physical barriers to their distribution. *(From Hamblin, W. K. 1992.* Earth's Dynamic Systems, *6th ed. New York: Macmillan)*

happening today, producing the Himalayan Mountains (the highest mountains in the world) and the Tibetan Plateau.

Understanding Plate Tectonics Solves Long-Standing Geologic Problems. Reconstruction of what the supercontinent Pangaea looked like about 200 million years ago has cleared up two interesting geologic problems:

- Occurrence of the same fossil plants and animals on different continents that would be difficult to explain if they had not been joined in the past (see Figure 2.18).
- Evidence of ancient glaciation on several continents, with inferred directions of ice flow, that makes sense only if the continents are placed back within Gondwanaland (southern Pangaea) as it was before splitting apart (see Figure 2.19).

2.6 How Plate Tectonics Works: Putting It Together

Driving Mechanisms That Move Plates. The primary source of energy that drives plate tectonics is energy from the molten interior of Earth (see Section 2.1 and Figure 2.7). Convection of the mantle heated by the core has kept Earth tectonically active for several billion years and will likely continue for several billion more years.[13] Now that we have presented the concept that new oceanic lithosphere is produced at mid-oceanic ridges because of seafloor spreading and that old, cooler plates sink into the

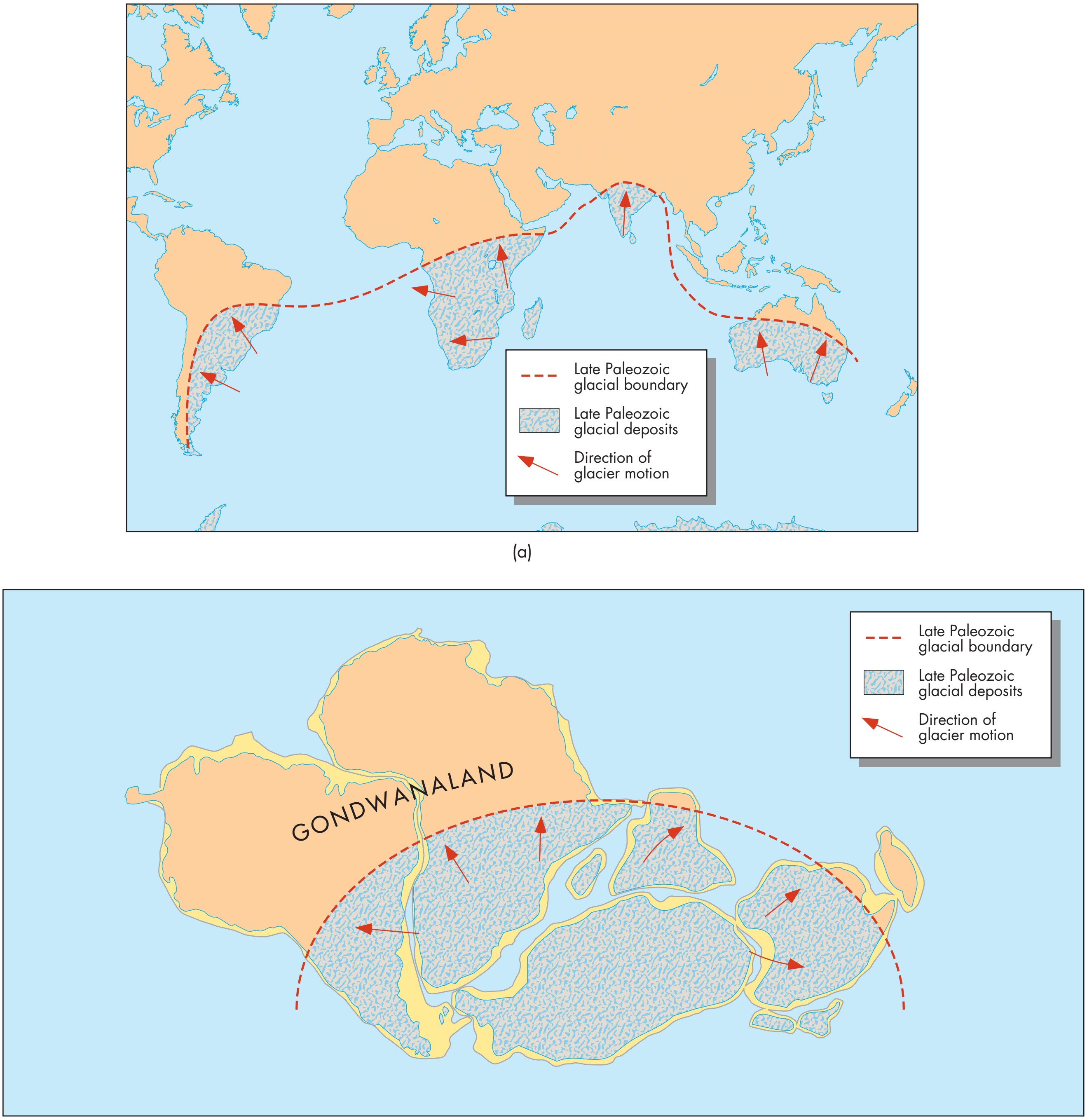


FIGURE 2.19 Glacial evidence for plate tectonics (a) Map showing the distribution of evidence for late Paleozoic glaciations. The arrows indicate the direction of ice movement. Notice that the arrows are all pointing away from ocean sources. Also, these areas are close to the tropics today, where glaciation would have been very unlikely in the past. These Paleozoic glacial deposits were formed when Pangaea was a supercontinent, before fragmentation by continental drift. (b) The continents are restored. (It is thought that continents had drifted north, away from the South Pole.) Notice that the arrows now point outward, as if moving away from a central area where glacial ice was accumulating. Thus, restoring the position of the continents produces a pattern of glacial deposits that makes much more sense. *(Modified after Hamblin, W. K. 1992.* Earth's Dynamic Systems, *6th ed. New York: Macmillan)*

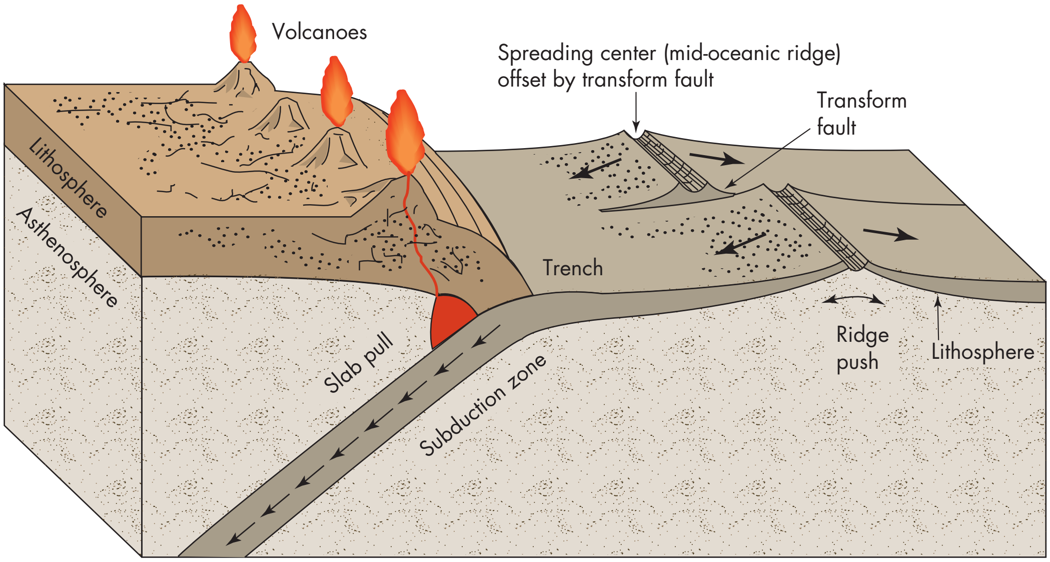


FIGURE 2.20 Push and pull in moving plates Idealized diagram showing concepts of ridge push and slab pull that facilitate the movement of lithospheric plates from spreading ridges to subduction zones. Both are gravity driven. The heavy lithosphere falls down the mid-oceanic ridge slope and subducts down through the lighter, hotter mantle. *(Modified after Cox, A., and Hart, R. B. 1986.* Plate Tectonics. *Boston: Blackwell Scientific Publications)*

mantle at subduction zones, let us evaluate the process of what causes the lithospheric plates to actually move and subduct. Figure 2.20 is an idealized diagram illustrating the two possible driving processes: ridge push and slab pull.[6]

The mid-oceanic ridges or spreading centers stand at elevations of 1 to 3 km (3,000 to 9,000 ft) above the ocean floor as linear, gently arched uplifts (submarine mountain ranges; see Figure 2.21) with widths greater than the distance from Florida to Canada. The total length of mid-oceanic ridges on Earth is about twice the circumference of Earth. Ridge push is a gravitational push, like a gigantic landslide, away from the ridge crest toward the subduction zone (the lithosphere slides on the asthenosphere). Slab pull results because, as the lithospheric plate moves farther from the ridge, it cools, gradually becoming denser than the asthenosphere beneath it. At a subduction zone, the plate sinks through the lighter, hotter mantle below the lithosphere, and the weight of this descending plate pulls on the entire plate, resulting in slab pull. Which of the two processes, ridge push or slab pull, is the more influential of the driving forces? Calculations of the expected gravitational effects suggest that ridge push is of relatively low importance compared with slab pull. In addition, it is observed that plates with large subducting slabs attached and pulling on them tend to move much more rapidly than those driven primarily by ridge push alone (e.g., the subduction zones surrounding the Pacific Basin). Thus, slab pull may be more influential in moving plates than ridge push.

2.7 Plate Tectonics and Environmental Geology

Plate Tectonics Affects Us All. The importance of the tectonic cycle to environmental geology cannot be overstated. Everything living on Earth is affected by plate tectonics. As the plates slowly move a few centimeters each year, so do the continents and ocean basins, producing zones of resources (oil, gas, and minerals), as well as earthquakes and volcanoes (Figure 2.4b). The tectonic processes occurring at plate boundaries largely determine the types and properties of the rocks upon which we depend for our land, our mineral and rock resources, and the soils on which our food is grown. For example, large urban areas, including New York and Los Angeles, are developed on very

FIGURE 2.21 Mid-Atlantic Ridge Image of the Atlantic Ocean basin showing details of the seafloor. Notice that the width of the Mid-Atlantic Ridge is about one-half the width of the ocean basin. *(Heinrich C. Berann/NGS Image Collection)*

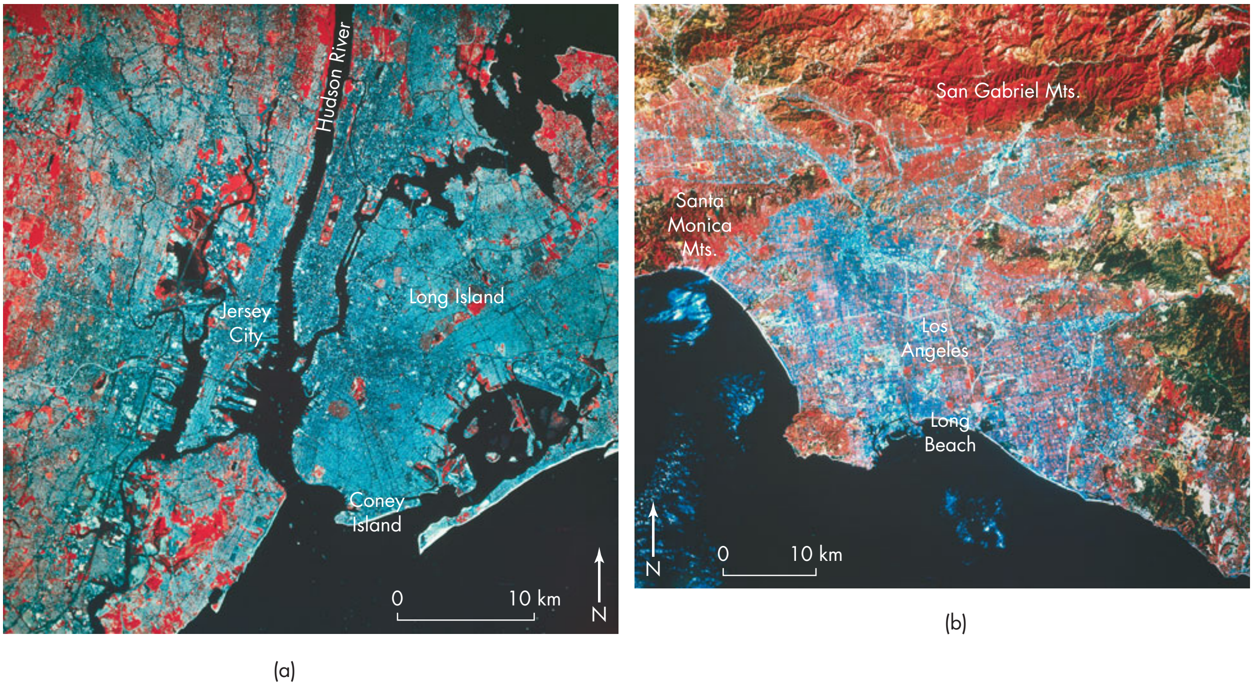


FIGURE 2.22 Los Angeles and New York Satellite images of (a) New York City and (b) the city of Los Angeles. Both are coastal cities; however, Los Angeles is surrounded by mountains, whereas New York is sited in a relatively low-relief area characteristic of much of the Atlantic coastal environment. For these images, healthy vegetation is red, urban development is blue, beaches are off-white, and water is black. *(SPOT Image/Photo Researchers, Inc.)*

different landscapes, but both have favorable conditions for urban development. New York (Figure 2.22a) is sited on the "trailing edge" of the North American plate, and the properties of the coastline are directly related to the lack of collisions between plates in the area. The divergent plate boundary at the Mid-Atlantic Ridge between North America and Africa is several thousand kilometers (over 1,500 mi) to the east. The collision boundaries between the North American and Caribbean plates and between the North American and Pacific plates are several thousands of kilometers (over 1,500 mi) to the south and west, respectively (see Figure 2.4a). The passive processes of sedimentation from rivers, glaciers, and coastal processes, depositing sediments on rifted and thinned continental crust, instead of the more active crustal deformation that produces mountains, have shaped the coastline of the eastern United States north of Florida. The breakup of Pangaea about 200 million years ago (Figure 2.17) produced the Atlantic Ocean, which, with a variety of geologic processes, including erosion, deposition, and glaciation over millions of years, eventually led to the development of the beautiful but subdued topography of the coastal New York area. In contrast, the Los Angeles metropolitan area is near the "leading edge" of the boundary between the North American and Pacific plates (Figure 2.10), characterized by active, vigorous crustal deformation (uplift; subsidence, or sinking of the ground's surface; and faulting) associated with the San Andreas fault, a transform boundary. The deformation has produced the Los Angeles Basin, rimmed by rugged mountains and uplifted coastline (Figure 2.22b).

Plate motion over millions of years can change or modify flow patterns in the oceans and the atmosphere, influencing or changing global climate, as well as regional variation in precipitation. Over several hundred million to several billion years, plate tectonics has formed, maintained, destroyed, and reformed ocean basins and continents. This cyclic nature of plate tectonics has been called the **Wilson Cycle**, named after the famous Canadian geologist and geophysists John Tuzo Wilson, who made significant contributions to plate tectonics. A summary of the

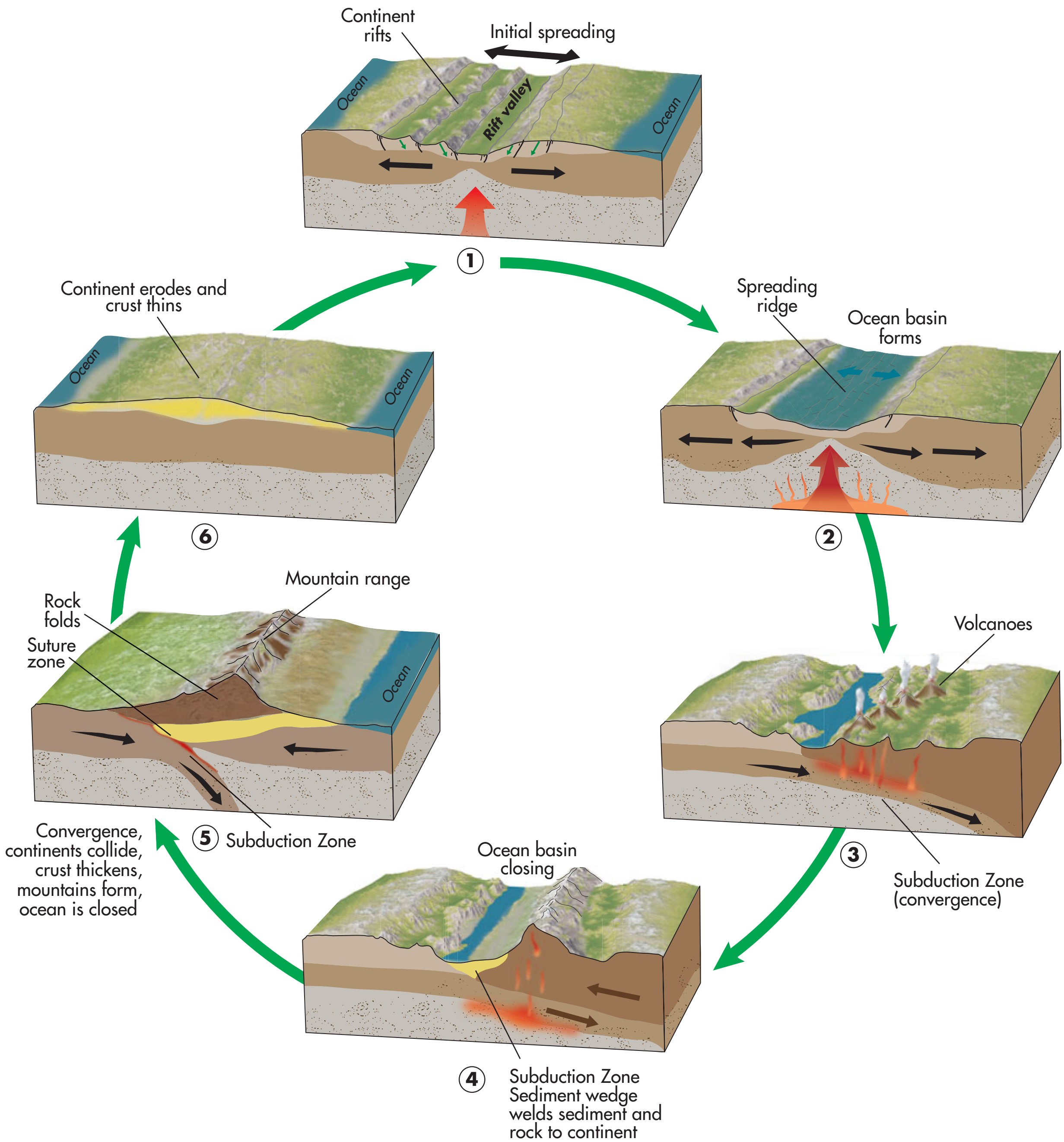


FIGURE 2.23 Wilson Cycle Idealized diagram of the Wilson Cycle, which is a relatively simple model of how Earth works. The cycle shown here is in six parts (stages), starting with a relatively thin-crusted continent worn down by erosion (1), fringed by oceans, that rifts (i.e., spreads apart) due to upwelling of magma, forming a spreading ridge (2); seafloor spreading forms an ocean basin. A subduction zone forms (3), initiating convergence, volcanic processes, and welding of sediment and rock to the continent; the ocean basin begins to close (4). With closing of the ocean basin, collision occurs (5) and high mountains form. Erosion of the continent and crustal thinning (6) is a final stage before another cycle is initiated (1). One cycle takes several hundred million years. Over the history of Earth, many cycles have formed, maintained, and destroyed ocean basins and rearranged and eroded continents.

Wilson Cycle as presented in recent years is shown in Figure 2.23.[13]

Plate tectonics affects the productivity of the land and its desirability as a place to live. Plate tectonics also determines, in part, what types of minerals and rocks are found in a particular region. We will explore how rocks and minerals are influenced by plate tectonics in Chapter 3.

Making The Connection

Linking the Opening Case History About the San Andreas fault to the Fundamental Concepts

Consider and discuss the following questions:

1. What is the link between population growth and the hazards from the San Andreas fault?
2. How does the San Andreas fault link to understanding the Earth as a system?

Summary

Our knowledge concerning the structure of Earth's interior is based on the study of seismology. Thus, we are able to define the major layers of Earth, including the inner core, outer core, mantle, and crust. The uppermost layer of Earth, known as the lithosphere, is relatively strong and rigid compared with the soft asthenosphere found below it. The lithosphere is broken into large pieces called plates that move relative to one another. As these plates move, they carry along the continents embedded within them. This process of plate tectonics produces large landforms, including continents, ocean basins, mountain ranges, and large plateaus. Oceanic basins are formed by the process of seafloor spreading and are destroyed by the process of subduction, both of which result from convection within the mantle.

The three types of plate boundaries are divergent (e.g., mid-oceanic ridges, spreading centers), convergent (e.g., subduction zones, continental collisions), and transform faults. At some locations, three plates meet in areas known as triple junctions. Rates of plate movement are generally a few centimeters per year.

Evidence supporting seafloor spreading includes paleomagnetic data, the configurations of hot spots and chains of volcanoes, and reconstructions of past continental positions.

The driving forces in plate tectonics are ridge push and slab pull. At present, we believe the process of slab pull is more significant than ridge push for moving tectonic plates from spreading centers to subduction zones.

Plate tectonics is very important in environmental geology because everything living on Earth is affected by it.

Key Terms

asthenosphere (p. 45)
continental drift (p. 46)
convection (p. 45)
convergent boundary (p. 50)
core (p. 43)
crust (p. 44)
divergent boundary (p. 49)
hot spot (p. 59)
isostasy (p. 52)
lithosphere (p. 45)
magnetic reversal (p. 56)
mantle (p. 43)
mid-oceanic ridge (p. 46)
Moho (p. 44)
paleomagnetism (p. 56)
plate tectonics (p. 46)
seafloor spreading (p. 46)
seismology (p. 45)
spreading center (p. 46)
subduction zone (p. 46)
submarine trench (p. 51)
transform boundary (p. 51)
triple junction (p. 53)
Wadati-Benioff zone (p. 49)
Wilson Cycle (p. 67)

Review Questions

1. What are the major differences between the inner and outer cores of Earth?
2. How are the major properties of the lithosphere different from those of the asthenosphere?
3. What are the three major types of plate boundaries?
4. What are the major processes that are thought to produce Earth's magnetic field?
5. Why has the study of paleomagnetism and magnetic reversals been important in understanding plate tectonics?
6. What are hot spots?
7. What is the difference between ridge push and slab pull in the explanation of plate motion?

Critical Thinking Question

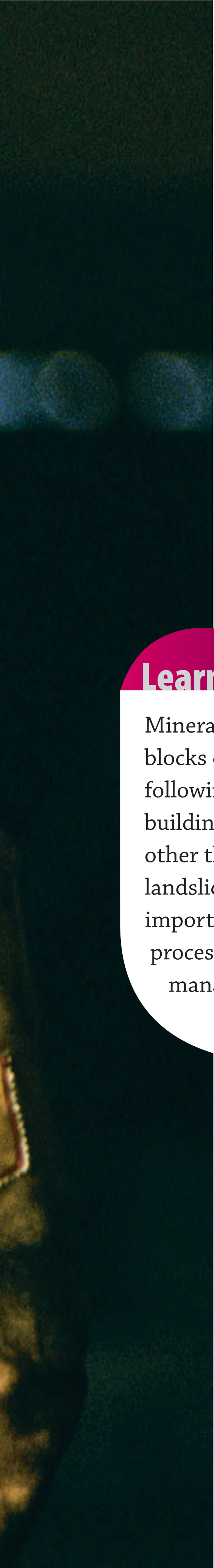
1. Assume that the supercontinent Pangaea (Figure 2.17) never broke up. Deduce how Earth processes, landforms, and environments might be different than they are today with the continents spread all over the globe. *Hint:* Think about what the breakup of the continents did in terms of building mountain ranges and producing ocean basins that affect climate and so forth.

Companion Website www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Workers in this factory using asbestos were not aware of the potential health hazards to which they were exposed. *(David & Peter Turnley/CORBIS)*



3

Minerals and Rocks

Written with the assistance of William Wise

Learning Objectives

Minerals and rocks are part of our inheritance from the geologic past. They are the basic building blocks of the solid Earth and are particularly important in environmental geology for the following reasons: (1) Minerals and rocks are among the basic resources we depend upon for building our homes, driving our automobiles, and manufacturing our computers, among many other things; (2) minerals and rocks play an important role in many Earth processes, such as landsliding, coastal erosion, and volcanic activity; (3) study of minerals and rocks provides important information concerning the history of Earth; and (4) knowledge of mineral and rock processes and properties is an integral part of understanding how Earth works and how to best manage Earth's resources. Mineral resources are discussed in detail in Chapter 15.

In this chapter we focus on the following learning objectives:

- **Understand minerals in terms of their chemistry and internal structure**
- **Know the major groups of important rock-forming minerals and their environmental significance**
- **Understand the rock cycle and how it interacts with plate tectonics**
- **Know the three rock laws**
- **Know the basic rock types and their environmental significance**
- **Know basic rock structures**

Case History

The Asbestos Controversy

For many people, the word *asbestos* is a red flag that signals a hazard to human health because asbestos may cause fatal lung disease. In response to the perceived hazard, people in the United States have spent large sums of money to remove asbestos from old buildings, such as schools and other public buildings, where it was used in ceiling and floor tiles and for insulation (**Figure 3.1**). The asbestos controversy is concerned with when and where asbestos should be removed, but first let us define asbestos and discuss the hazards it causes.

Asbestos is broadly defined as small, elongated mineral fibers that are present in certain silicate minerals. Silicate minerals and rocks are those that contain silicon (Si) and oxygen (O) in their chemical composition. Asbestos has proved to be a useful mineral/fiber, particularly because of its fire-retardant properties. It is also used in brake linings and in a variety of insulations. However, human exposure to asbestos has caused lung disease, including cancer. Realization of the health hazard led to efforts to reduce and remove asbestos or to ban it outright.

The mineral quartz, which is not asbestos but may be present in crushed rock as small mineral fragments or grains, is also considered a probable carcinogenic material to humans. As a result, any natural material in the United States containing 0.1 percent of free silica, including quartz, must display hazardous warning signs. Theoretically, trucks that transport crushed rocks need to carry warning signs; a truck driver transporting crushed stones in Delaware was issued a citation for not displaying such signs on his truck! A local Delaware paper reported facetiously that beaches composed of silica sand might also present a public health hazard, so warnings should be posted on the beaches. The author of the article went on to state that much misunderstanding has resulted from well-meaning efforts to extrapolate data from environmental toxicity studies without understanding common natural characteristics of minerals.[1,2] The author's point was that, although sand is composed of quartz, it is in the form of hard, rounded particles, not potentially hazardous fibrous dust.

The different types of asbestos are not equally hazardous. In fact, exposure to "white asbestos," or chrysotile, the variety most commonly used in the United States, is evidently not very harmful. On the other hand, "blue asbestos," the mineral crocidolite, is known to cause lung disease.[2]

A good deal of fear is associated with nonoccupational exposure to asbestos, particularly exposure of children. Identifying potentially hazardous blue asbestos in schools, public buildings, and homes and then removing or covering it to avoid human exposure is an important goal.

3.1 Minerals

What Is a Mineral? A mineral is a naturally occurring, solid Earth material that has formed by geologic processes. A more precise definition will follow, after we introduce some basic chemistry necessary for deeper understanding of minerals. For now, think of minerals as the building blocks of rocks that form the solid framework of Earth's crust.

Atoms and Elements

The study of atoms and elements of importance to geologic processes is a part of *geochemistry*, the study of the chemistry of Earth. Geochemistry includes the study of the natural distribution of chemical elements in minerals, rocks, soils, water, and the atmosphere, along with the transfer of atoms through the environment. Let us start with some definitions.

All matter—including rocks, minerals, water, and you—is composed of *atoms*. An atom is the smallest part of a chemical element that can take part in a chemical reaction or combine with another atom. An element is a chemical substance composed of identical atoms that may not be separated into different substances by ordinary chemical means. An atom of a particular element is denoted by its atomic symbol, often the abbreviation of the first letter or first and second letters

Funds spent to remove hazardous blue asbestos constitute a good investment in environmental health. Large amounts of money have been spent to remove white asbestos, which is not very hazardous and may not always require removal. Deciding whether to remove asbestos requires the careful study of fibrous minerals and rocks in the context in which they are used; only then can we understand their potential toxicity to people and other living things. In the larger context, the asbestos controversy emphasizes the need to know more about the minerals we use in modern society and how they are linked to the environment.

(a)

(b)

FIGURE 3.1 Asbestos (a) Woman wearing protective clothing while inspecting asbestos. *(Rene Sheret/Stone Allstock/Getty Images)* (b) Sample of white asbestos, showing the fluffy, fibrous nature of this commercial-grade asbestos. The scale along the bottom is in millimeters. *(From Skinner, H. C. W., Ross, M., and Frondel, C. 1988.* Asbestos and Other Fibrous Materials: Mineralogy, Crystal Chemistry, and Health Effects. *New York: Oxford University Press)*

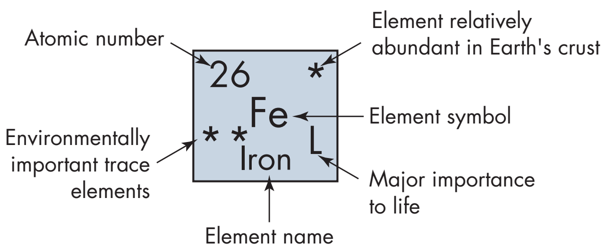
of the English or Latin name of that element.[3] For example, the atomic symbol for an atom of carbon is C, and oxygen's atomic symbol is O. The periodic table (**Table 3.1**) includes a list of known elements.

Conceptual Model of an Atom

Idealized diagrams of an atom are shown in **Figure 3.2** (page 77). These models show the core, or nucleus, of an atom and three subatomic particles: *protons*, *neutrons*, and *electrons*. The nucleus of the atom is composed of protons, which carry a positive charge, and neutrons, which carry no charge. Electrons carry a negative charge and are found outside the nucleus. The number of protons in the nucleus of an atom for a particular element is unique and defines its *atomic number*, as listed in Table 3.1. For example, hydrogen has 1 proton in its nucleus, oxygen has 8 protons, silicon has 14, gold has 79, uranium has 92, and so on. Also shown in Table 3.1 are those elements that are relatively abundant in the minerals and rocks of Earth's crust, such as silicon, oxygen, aluminum, and iron; those of major importance to life, including carbon, oxygen, and nitrogen; and those that have environmental importance in very small amounts, referred to as *trace elements*, such as cobalt, zinc, lead, and uranium.

An atom may be conceptualized as a nucleus surrounded by an electron cloud (Figure 3.2a).

TABLE 3.1 Periodic Table of the Elements Showing Elements That Are Relatively Abundant in Earth's Crust and Some Environmentally Important Trace Elements



1 H L Hydrogen																	2 He Helium
3 Li * * Lithium	4 Be Beryllium											5 B Boron	6 C L Carbon	7 N L Nitrogen	8 * O L Oxygen	9 F * * Fluorine	10 Ne Neon
11 * Na L Sodium	12 * Mg L Magnesium											13 * Al Aluminum	14 * Si * * Silicon	15 P Phosphorus	16 S L Sulfur	17 Cl L Chlorine	18 Ar Argon
19 * K L Potassium	20 * Ca L Calcium	21 Sc Scandium	22 Ti Titanium	23 V * * Vanadium	24 Cr * * Chromium	25 Mn * * Manganese	26 * Fe * * L Iron	27 Co * * L Cobalt	28 Ni * * Nickel	29 Cu * * L Copper	30 Zn * * L Zinc	31 Ga Gallium	32 Ge Germanium	33 As * * Arsenic	34 Se * * Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo * * L Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd * * L Cadmium	49 In Indium	50 Sn * * Tin	51 Sb Antimony	52 Te Tellurium	53 I * * Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57 La Lanthanum	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg * * Mercury	81 Tl Thallium	82 Pb * * Lead	83 Bi Bismuth	84 Po * * Polonium	85 At Astatine	86 Rn * * Radon
87 Fr Francium	88 Ra * * Radium	89 Ac Actinium															
				58 Ce Cerium	59 Pr Praseo-dymium	60 Nd Neo-dymium	61 Pm Prome-thium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolin-ium	65 Tb Terbium	66 Dy Dyspro-sium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
				90 Th Thorium	91 Pa Protac-tinium	92 U * * Uranium	93 Np Neptunium	94 Pu * * Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Califor-nium	99 Es Einstein-ium	100 Fm Fermium	101 Md Mendele-vium	102 No Nobelium	103 Lr Lawrenc-ium

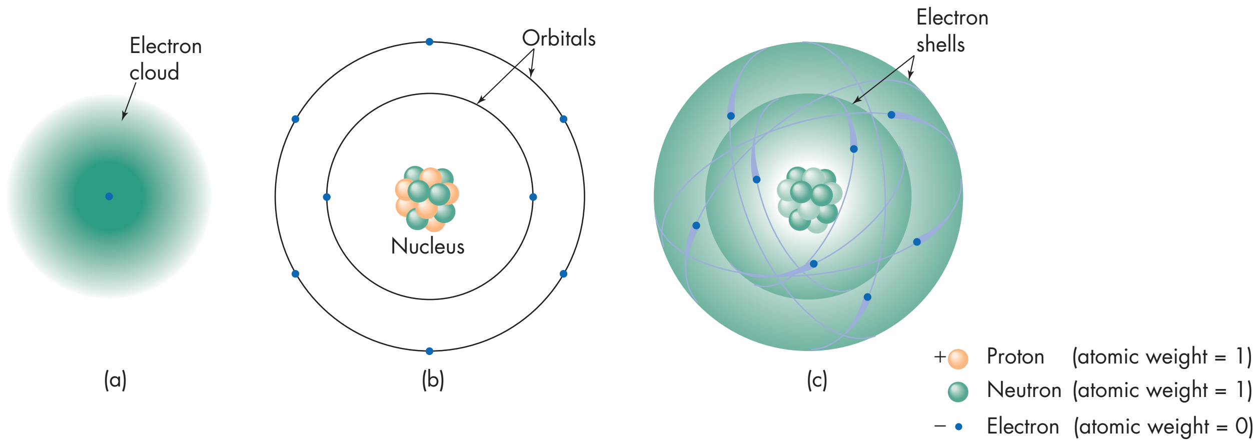


FIGURE 3.2 The atom (a) Idealized diagram showing the basic structure of an atom as a nucleus surrounded by an electron cloud. (b) This conceptualized view is only an approximation or model showing the nucleus of the atom surrounded by orbiting electrons. (c) A more realistic view of an atom consists of electron shells surrounding the nucleus. (Shown here is oxygen; the size of the nucleus relative to electron shells has been greatly exaggerated in order to be viewed.) *(After Press, F., and Siever, R. 1994.* Understanding Earth. *New York: W. H. Freeman)*

Electrons can also be depicted as revolving in orbits around the nucleus, much as Earth and our neighboring planets revolve around the Sun (Figure 3.2b). Although this is a satisfactory model for conceptualizing what an atom looks like, it is too simple and inaccurate from a mathematical standpoint.[3] Electrons are actually arranged in energy levels, or shells, around the nucleus (Figure 3.2c). Because the electrons are negatively charged, those closest to the positively charged nucleus are held more tightly than those in the outer shells.

Although electrons carry a negative charge, they have a very small mass compared with protons and neutrons. As a result, almost the entire mass of an atom is concentrated in the nucleus. The sum of the number of neutrons and protons in the nucleus of an atom is known as the *atomic mass number*. Because neutrons carry no charge, an atom is electrically balanced when the number of protons is equal to the number of electrons. However, atoms may gain or lose loosely bound electrons that are in the outer shells. An atom that has lost or gained electrons is known as an *ion*. If an atom loses electrons, it becomes positively charged and is known as a *cation*. For example, potassium, atomic symbol K, becomes K^+ after losing one electron. If an atom gains electrons, it becomes negatively charged and is known as an *anion*. Oxygen, atomic symbol O, becomes O^{2-} after gaining two electrons.

Isotopes

What Is an Isotope? Atoms of the same element always have the same atomic number. However, they may have a variable number of neutrons and, therefore, a variable atomic mass number. Two atoms of the same element with a different number of neutrons in the nucleus are known as *isotopes*. Two isotopes of the element carbon, which is the building block of the living world, are $^{12}_{6}C$ and $^{13}_{6}C$. Atoms of both of these isotopes have an atomic number of 6, but their atomic mass numbers are 12 and 13, respectively. These isotopes are sometimes written as C-12 and C-13. Of the two, C-12 is the common isotope.

Why Are Isotopes Important in Studying the Environment? It is a triumph of science that so much has been learned from studying isotopes. For example, some isotopes are called radioisotopes because they are unstable and undergo nuclear decay (i.e., spontaneously change and emit nuclear radiation). These are discussed in Chapter 16, with nuclear energy. Other elements have stable isotopes that do not undergo nuclear decay. For example, oxygen has two stable isotopes, $^{16}_{8}O$ and $^{18}_{8}O$. Study of the abundance of these two oxygen isotopes in seawater, glacial ice (frozen water), and very small marine organisms known as forminifera has provided exciting evidence about global climate change and how much

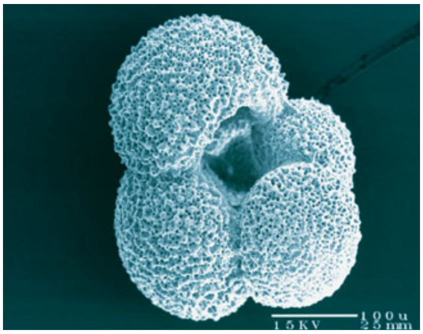


FIGURE 3.3 Forminifera A type of planktonic animal useful for extracting oxygen isotope information. Specimen taken from ocean floor sediments. Distance across is about 0.1 mm. *(Courtesy of Tessa Hill)*

glacial ice has been present at different times in Earth history (**Figure 3.3**). $^{16}_{8}O$ is lighter than $^{18}_{8}O$ so is preferentially evaporated with water (H_2O) from the ocean. During times when lots of glacial ice is on the land, the ocean is relatively depleted in $^{16}_{8}O$, and forminifera then have less $^{16}_{8}O$ in the mineral material of their shells. Forminifera occur as fossils with sediment that accumulates on the ocean floor. When fossil forminifera are collected and dated, and the relative amounts of the two oxygen isotopes are determined, we can infer how much ice was on land and whether the climate was warm or cold.

Mineral Chemistry: Compounds

A **mineral** is formally defined as an element or a chemical compound that must[4]:

1. Be naturally formed. This requirement excludes human-made substances such as human-made diamonds.
2. Normally be a solid. This requirement excludes most fluids and all gases.
3. Have a characteristic chemical formula.
4. Have a characteristic crystalline structure, in most cases. Although some geologists require that the substance have a crystalline structure, the definition of *mineral* was revised in the mid-1990s to include some noncrystalline solids and even some liquids, such as mercury.

Minerals can be either elements or compounds. We discussed elements earlier. A compound is a substance composed of two or more elements that can be represented by a chemical formula, such as PbS for lead sulfide. Naturally occurring PbS is the mineral *galena* that we mine to obtain lead. Thus, minerals may be composed of either a single element, such as the mineral diamond, which is composed of carbon (C), or several elements in a compound such as the mineral galena, which is composed of lead sulfide (PbS).

Minerals and Chemical Bonding

The atoms that constitute a mineral are held together by *chemical bonding*. Bonding results from attractive forces between atoms, sharing of electrons, or both. Types of bonds determine some of the primary physical properties of minerals; they explain in part, for example, why diamonds and graphite have the same chemical formula of pure carbon (C) but are so different.

There are four main types of chemical bonds in minerals: covalent, ionic, van der Waals, and metallic. *Covalent bonds* form when atoms share electrons. For example, diamond, one of the hardest substances on Earth, is composed of covalently bonded carbon atoms (**Figure 3.4**). Gem-quality diamonds are clear, hard crystals that jewelers may cut to form beautiful gemstones of high value. Covalent bonds are stronger than *ionic bonds*, which form because of an attraction between negatively and positively charged ions. An example of an ionic bond is the attraction of Na^+ and Cl^- ions, forming sodium chloride, the mineral halite. Compounds with ionic bonds are much more soluble and easily dissolved in water than are those with covalent bonds. Therefore, minerals with ionic bonds tend to be chemically active and mobile in the environment. *van der Waals bonds* involve a weak attraction between chains or sheets of ions that themselves are likely to be bonded by stronger covalent and ionic bonds. As previously mentioned, the mineral graphite, like diamond, is composed of pure carbon. However, the similarity between graphite and diamond ends there. Graphite is black and consists of soft sheets of carbon atoms that easily *part*, or break from one another (a mineral property called *cleavage*; see Appendix A). Graphite is the "lead" used in pencils. It is also a good dry lubricant, sprayed as a dust into door locks to help the parts of the lock move freely. *Metallic bonds* form between metal atoms. Gold contains metallic bonds. Gold's properties, such as its ability to conduct an electrical current, and malleability,

(a)

(b)

FIGURE 3.4 Diamond (a) Diamond crystal. *(Joel Arem/Photo Researchers, Inc.)* (b) Idealized diagram of the internal structure of diamond, with balls representing carbon atoms joined by rods representing strong covalent bonds. *(Charles D. Winters/Photo Researchers, Inc.)*

the ability to form paper-thin sheets, are both due to metallic bonds. In a metallic bond, electrons are shared by all atoms of the solid rather than by only specific atoms, as in covalent bonds. The electrons can flow, making gold both an excellent conductor of electricity and easy to pound into a thin sheet.[5] As a result, gold is in high demand for electronic processing.

When learning about chemical bonding of minerals, keep in mind that you are dealing with a complex subject: Bonding in minerals may not be strictly of a particular type but may have properties of the various types. Thus, for a particular mineral, more than one type of bond is often present.[5]

Crystalline Structure of Minerals

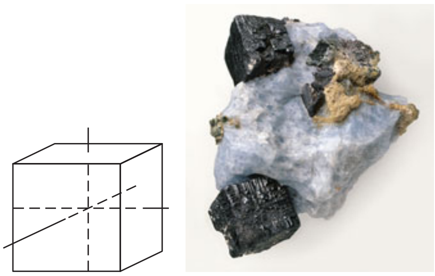
Now that we know that chemical bonds hold the atoms of minerals together, let's consider the term *crystalline*. *Crystalline* refers to the orderly regular repeating geometric patterns of atoms found in most minerals. The smallest unit of this geometric pattern in a crystal is called the *unit cell*. A crystal is composed of stacking unit cells.[3] The internal structure for a given mineral typically contains a particular symmetry that determines the external form of the crystal. **Figure 3.5** shows some of the common shapes of crystals for selected minerals.

The internal crystal structure or framework for halite is shown in **Figure 3.6**. The structure is a cube with sodium ions at the corners and chlorine ions at intermediate positions in the *crystal lattice*, the framework that defines the regular geometric pattern of atoms in a crystal. Notice that in Figure 3.6b, which is drawn to relative scale, the sodium ions are approximately half the size of the chloride ions. The length along one of the edges is approximately 0.56 nanometers (1 nm = 0.000000001 m). This distance is so short that it needs to be magnified approximately 1 million times to be the same size as a grain of sand or the head of a pin.

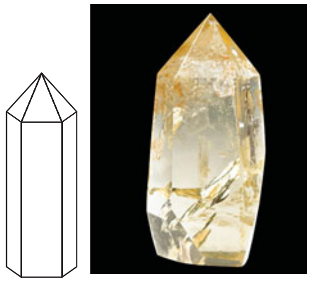
3.2 Important Rock-Forming Minerals

Although there are more than 4,000 minerals, only a few dozen are common constituents of Earth materials on or near Earth's surface. These few minerals are often important to many environmental concerns and are necessary in identifying most Earth materials we know as rocks, which are aggregates of one or more minerals. Some selected minerals are shown in **Figure 3.7** (page 81).

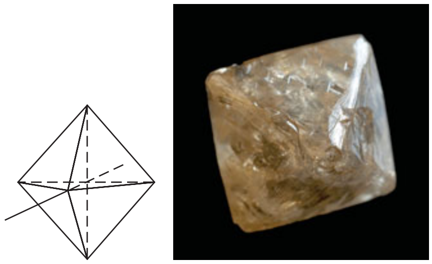
Determining a mineral's chemical composition and crystalline structure requires the use of sophisticated instruments. When we identify minerals from hand specimens, samples that you can hold in your hand, we also use appearance and some physical properties to assist us. Mineral properties, with their chemical compositions, are defined in Appendix A, with a table of some of the common minerals likely to be encountered in environmental geology work. Finally, **weathering**, the way that a mineral breaks down by physical and chemical



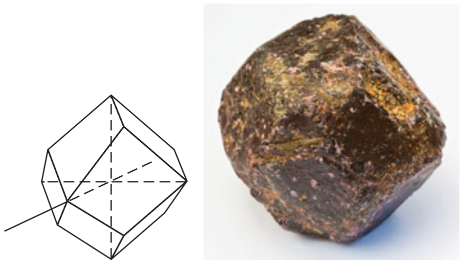
(a) Cube
4-sided crystal
mineral examples:
halite, pyrite



(b) Hexagon
6-sided crystal
mineral example:
quartz

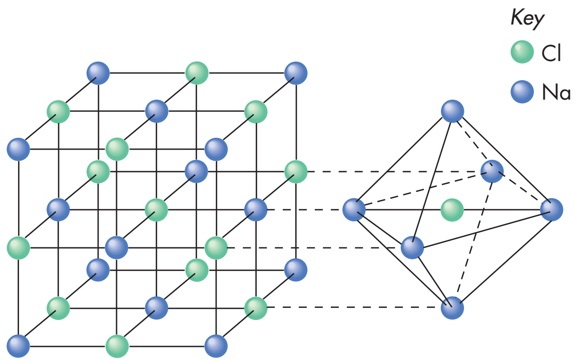


(c) Octahedron
8-sided crystal
mineral examples:
diamond, fluorite

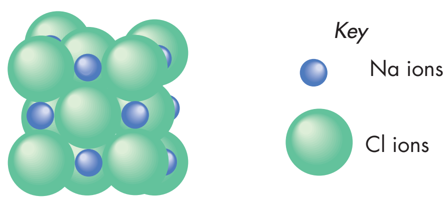


(d) Dodecahedron
12-sided crystal
mineral example:
garnet

FIGURE 3.5 Shapes of crystals Some common shapes of crystals for selected minerals. *([a] Dorling Kindersley/Getty Images; [b] Zelenka68/Dreamstime.com; [c] Zbynek Burival/iStockphoto; [d] Sean Curry/iStockphoto)*



(a)



(b)

FIGURE 3.6 Crystal structure (a) The structure of sodium chloride, showing the arrangement of six sodium (Na^+) ions around one chloride (Cl^-) ion. (b) The same structure with ions drawn to their relative sizes. *(After Gribble, C. D., ed. 1988.* Rutley's Elements of Mineralogy, *27th ed. Boston: Unwin Hyman)*

processes at or near the surface of Earth, is important in forming sediments and soil (see A Closer Look: Weathering).

Although it is not often stated, geologists learn to identify the common minerals in hand specimens or under a microscope through the mental process of pattern recognition, based on clues such as color, specific gravity, crystal form, cleavage, and so on. After careful examination of a number of samples, you learn to recognize a particular mineral, and the identification can be verified by a simple test or two. Recognition of the important rock-forming minerals is an important skill for a geologist.

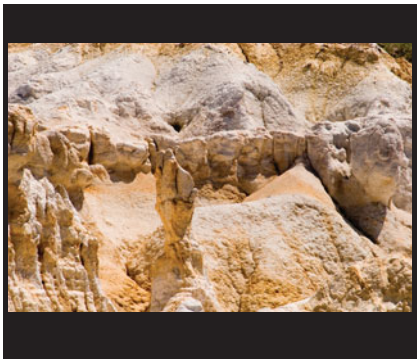
The important groups of rock-forming minerals are summarized in Table 3.2 (on page 83). Each group is based primarily upon chemistry, and this abbreviated list serves as a summary for our discussion of types of minerals. We will now discuss each of the major mineral groups.

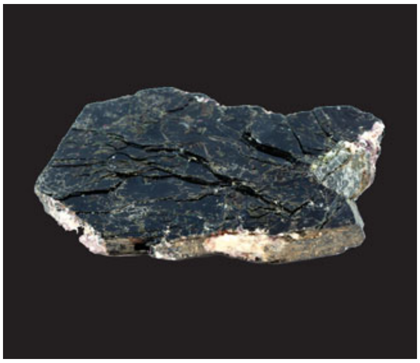
Silicates

The Earth's crust by weight is composed of oxygen (45 percent) and silicon (27 percent). These two elements, in combination with a few others, including aluminum (8 percent), iron (6 percent), calcium

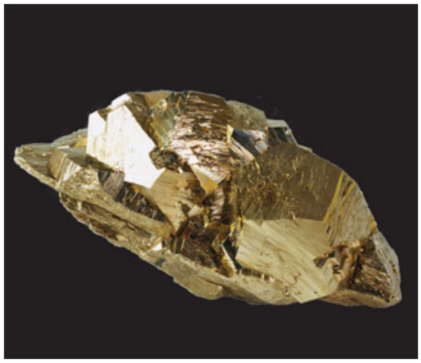

(a)


(b)


(c)


(d)


(e)


(f)

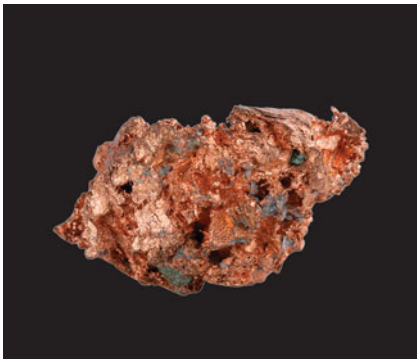

(g)

FIGURE 3.7 Some common minerals Shown are hand specimens: (a) Cluster of quartz crystals from Brazil. Some are colorless and some are rose colored. Quartz is a very hard, common rock-forming mineral. *(Ricardo Saraiva/Dreamstime.com)* (b) One of the several varieties of feldspar, the most common rock-forming mineral in Earth's crust. *(Stuart Cohen/Comstock)* (c) Yellow and pink clay minerals on rock. These are only two examples of the many clay minerals that, when present in soils, may exhibit undesirable properties such as low strength, high water content, poor drainage, and high shrink–swell potential. *(Tim Pleasant/Shutterstock)* (d) The dark mineral is the black mica called biotite. It is a common mineral in granitic rocks as well as some metamorphic rocks. *(Tyler Boyes/Shutterstock)* (e) Calcite, the abundant mineral in limestone and marble. Limestone terrain is associated with caverns, sinkholes, subsidence, and potential water pollution and construction problems. *(efesan/iStockphoto)* (f) Pyrite (fool's gold) is iron sulfide, a common mineral associated with ore deposits and coal that reacts with water and oxygen to form sulfuric acid. *(Gary Ombler/Dorling Kindersley/Getty Images)* (g) Fragment of native copper. *(Zelenskaya /Shutterstock)*

(5 percent), magnesium (3 percent), sodium (2 percent), and potassium (2 percent), account for the chemical composition of minerals that make up about 98 percent by weight of Earth's crust. Astoundingly, about 94 percent by volume of the crust is oxygen! Geologists commonly report the abundance of a material by either mass (weight) or volume. Although mass is normally measured in kilograms, the correct unit for weight is Newtons. Newtons are calculated as kilograms multiplied by gravity; since gravity is a constant on Earth, we often ignore it in common uses of everyday life. Therefore, in Europe cheese is sold by the kilogram, and in the United States it is sold by the pound. Whatever the units, we all know that a cup filled with Styrofoam weighs less than a cup of sand. *Volume* refers to the amount of space a material takes up. One cubic meter of Styrofoam and 1 cubic meter of sand have the same volume, but the sand is much heavier than the Styrofoam.

Minerals that include the elements silicon (Si) and oxygen (O) in their chemical composition are called *silicates*; these are the most abundant of the rock-forming minerals. The basic building block of

A Closer Look

Weathering

What Is Weathering? Briefly defined, *weathering* is the breaking apart or chemical decomposition of minerals and rocks at or near the surface of Earth by physical, biological, and chemical processes. Weathering processes are important for various reasons:

- They are some of the primary processes involved in the formation of soil (see Chapter 17).
- They prepare—that is, reduce in size and weaken—Earth material for easier transport by running water or slope processes, such as landslides.
- Through chemical decomposition of some rock types, such as limestone, discussed in Section 3.6, they produce characteristic landforms, such as surface pits or sinkholes, and subsurface voids, such as caverns (see Chapter 13).
- They are responsible for the transformation of minerals, such as transforming feldspars to clay minerals.

As stated above, the processes involved in weathering are physical, chemical, and biological, or some combination of these. For example, physical weathering or breaking of rocks may be caused by frost action; water in rock fractures freezes and expands, breaking apart individual mineral grains from each other. Examples of biologically induced weathering include burrowing of animals and microbial digestion of rocks by a variety of organisms. The term *chemical weathering* refers to the partial dissolution of rocks and their minerals by chemical reactions, usually in the presence of natural acidic solutions such as carbonic acid, commonly found in soils. Even rainwater is slightly acidic because carbon dioxide in the atmosphere combines with the water to produce a weak carbonic acid ($CO_2 + H_2O \rightarrow H_2CO_3$). Stronger acids may be formed as a result of water's mixing with sulfide minerals to form sulfuric acid. The net result from weathering is that, near the surface of Earth, rocks are broken down or dissolved. This breakdown prepares the sediment that commonly constitutes the load that rivers transport to a lake or an ocean. In environmental geology, when describing Earth materials such as minerals, rocks, and soils at a site, one must carefully evaluate how those materials have weathered and where the weathered products, such as clay minerals, are concentrated.

You are probably familiar with the fight to control rust on your car, bicycle, or tools. Rust results from the oxidation, a chemical weathering process, of iron. Rust is composed of a group of minerals collectively named *limonite*, often a soft earthy material with a yellow-brown color. Rust weakens metals, reducing their strength and usefulness. Similarly, the chemical weathering of an otherwise strong rock by the "rusting" of iron-bearing minerals or formation of clay along fractures in the rock may weaken the rock (**Figure 3.A**). The weathered rock will not be as strong or as desirable for a foundation material for a structure such as a concrete dam and may be likely to fail by a landslide.

FIGURE 3.A Chemical weathering Weathered clay (iron stained orange) and thin lighter layer of calcite and gypsum minerals that form along weathered layers can weaken rock. *(Edward A. Keller)*

TABLE 3.2 Rock-Forming Minerals by Groups, Based Mostly on Chemistry

Mineral Group	Examples	Chemical Formula	Comments
Silicates	Quartz	SiO_2	Common
	Plagioclase feldspars	$(Na, Ca)Al(Si, Al)_2 O_8$	Very common
	Pyroxene	$(Ca, Mg, Fe)_2 Si_2O_6$	Ferromagnesian mineral
Carbonates	Calcite	$CaCO_3$	Main minerals in limestone and marbles
	Dolomite	$(Ca, Mg)CO_3$	
Oxides	Hematite	Fe_2O_3	Primary ore of iron
	Bauxite	Hydrous aluminum oxides	Primary ore of aluminum
Sulfides	Pyrite	FeS_2	Major constituent of acid mine drainage
	Galena	PbS	Primary ore of lead
Native elements	Gold	Au	Precious metal, industrial uses
	Diamond	C	Jewelry, industrial uses
	Sulfur	S	Used to produce sulfuric acid

Note: A more extensive list is in Appendix A.

all silicate minerals is the pyramid-shaped silicon–oxygen tetrahedron composed of relatively large oxygen ions at the corners, with the small silicon ion in the center (**Figure 3.8**). The tetrahedron may be present in a particular mineral framework as isolated tetrahedra, single or double chains, sheets, or complex networks (**Figure 3.9**).[3] The silicon–oxygen tetrahedra combine with other elements, such as calcium, magnesium, sodium, and aluminum, to form the various silicate minerals. The arrangement of the silicon–oxygen tetrahedra in their various forms determines the properties of minerals (see Figures 3.8 and 3.9). The most important rock-forming silicate minerals or mineral groups are quartz, the feldspar group, micas, and the ferromagnesian group.

Quartz. *Quartz*, a form of silicon dioxide (SiO_2) with a network structure of silicon–oxygen tetrahedra, is one of the most abundant minerals in the crust of Earth. It can usually be recognized by its hardness, which is greater than that of glass, and by the characteristic way it fractures—conchoidally (**Figure 3.10**). Pure quartz is colorless (i.e., clear), but most quartz crystals contain impurities that can make them white, rose, purple, or smoky black, among other colors (Figure 3.7a). Some of these colored varieties are semiprecious gemstones, such as purple amethyst. Large six-sided, clear, pointed crystals of quartz are abundant in nature and are often sold as crystals. Because it is very resistant to the natural weathering processes and the processes that transport mineral grains, such as in rivers, quartz is a common mineral in river and beach sands.

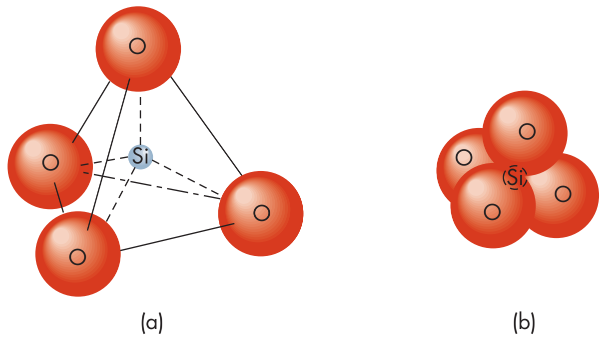


FIGURE 3.8 Silicon–oxygen tetrahedron (a) Idealized diagram of the silicon–oxygen tetrahedron. This view is expanded to show the relatively large oxygen ions at the corners of the tetrahedron with the small silicon ion in the center. Chemical bonds are represented by the dashed lines between silicon and oxygen ions. (b) Diagram of the tetrahedron more as it is found in nature, with the oxygen ions touching each other. The silicon ion is the dashed circle in the central part of the tetrahedron. *(After Dietrich, R. V., and Skinner, V. J. 1979.* Rocks and Rock Minerals. *New York: John Wiley)*

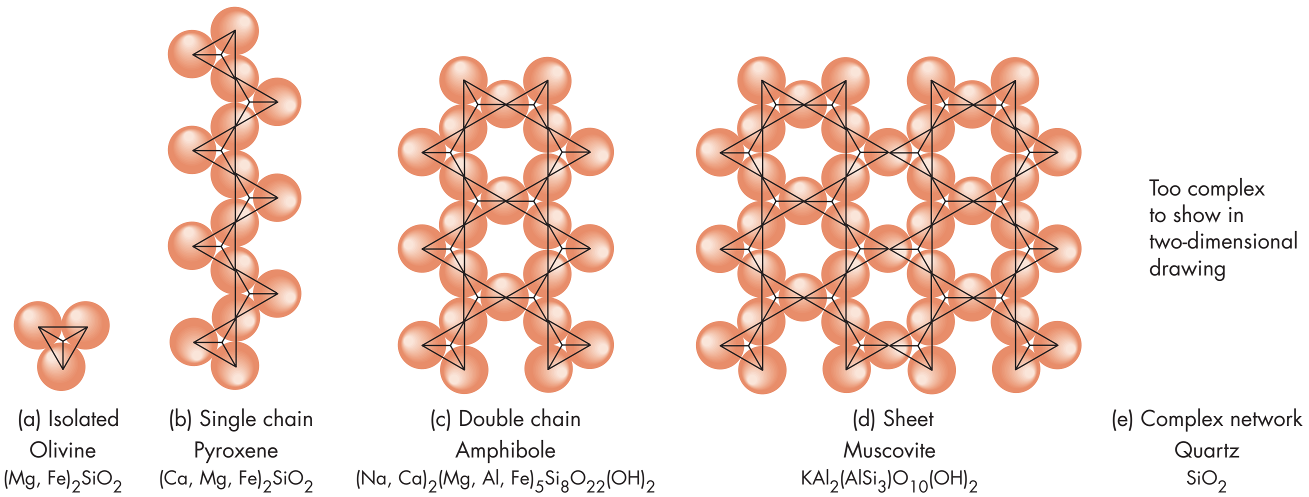


FIGURE 3.9 Linking silicon–oxygen tetrahedron Idealized diagram showing several ways silicon–oxygen tetrahedra may be linked. *(After Press, F., and Siever, R. 1994.* Understanding Earth. *New York: W. H. Freeman)*

Feldspars. *Feldspars* are aluminosilicates, containing silicon (Si), oxygen (O), and aluminum (Al) in combination with potassium (K), sodium (Na), or calcium (Ca) in a network structure of silicon–oxygen tetrahedra. The most abundant group of rock-forming minerals, constituting 60 percent of Earth's crust, feldspars are commercially important in the ceramics and glass industries. They are generally gray or pink and are fairly hard (Figure 3.7b).

There are two major types of feldspar: (1) alkali feldspars, $(Na, K)AlSi_3O_8$, which represent several feldspar minerals rich in potassium (K-feldspar) or sodium; and (2) plagioclase feldspars, $(Na, Ca)Al(Si, Al)Si_2O_8$, which are a series of minerals ranging from sodium rich to calcium rich. In the chemical formulas, the elements in parentheses, as for example the (Na, Ca) in plagioclase, represent elements that can substitute for one another.

Feldspars may weather chemically to form clay minerals (Figure 3.7c) with important environmental implications (see both A Closer Look: Weathering and A Closer Look: Clay).

Mica. *Mica* is a name for a group of important rock-forming minerals formed from sheets of silicon–oxygen tetrahedra, including the colorless mica, muscovite, $KAl_2(AlSi_3)O_{10}(OH)_2$, and the ferromagnesian mica, biotite, defined below. The micas are distinguished by a perfect *basal cleavage*—that is, they cleave parallel to the base of the crystal and peel into sheets. The mineral muscovite was used in pioneer times as window material and later in doors of ovens, enabling one to see what was cooking.

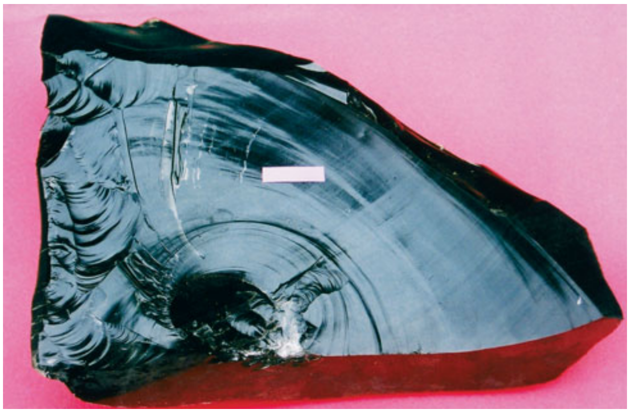


FIGURE 3.10 Conchoidal fractures Conchoidal fractures looks like arcs of circles. This photograph shows such fractures in natural volcanic glass (obsidian). Quartz also fractures conchoidally. The bar is 2.5 cm (1 in.) long. *(Edward A. Keller)*

Ferromagnesian Minerals. *Ferromagnesian minerals* are a group of silicates in which the silicon and oxygen combine with iron (Fe) and magnesium (Mg). These are the dark (black, brown, or green) minerals in most rocks. Black mica, biotite, $K(Mg, Fe)_3AlSi_3O_{10}(OH)_2$, is formed from sheets of the silicon–oxygen tetrahedra (Figure 3.7d). Three other important groups of ferromagnesian minerals used to identify igneous rocks, or rocks

A Closer Look: Clay

The term *clay* is an important term in environmental geology and can be defined in several ways. We use the term *clay-sized* particles to describe particles that are less than 0.004 mm in diameter—very small indeed. We also refer to clay as very fine mineral fragments defined in terms of chemical composition and internal crystal structure. The numerous clay minerals may be classified into several groups, based on chemical characteristics and atomic structure. Some clays take in a lot of water and expand upon wetting, a topic discussed in Chapter 17.

People have been using clays for thousands of years because they may be molded to form anything from crude pots to fine china to building blocks, including brick or sun-dried adobe. Because some clay minerals have a high capacity for absorbing liquids, they have a variety of uses for medicine and industry. For example, some "kitty litter" is composed primarily of clays. Clay minerals are used as a filler for paper, and clay is also used to coat paper, particularly when a glossy finish is desired.

Clays are so often used in industrial processes that most of them have been synthesized from basic ingredients. When found in nature, clays are generally a warning to the environmental geologist. For example, clays may fill in fractures of rocks, thereby weakening the rocks. They may also be present in particular soil layers, where they may present problems in stabilizing a slope or preparing for the foundation of a building.

formed from the solidification of magma, are *olivine*, $(Mg, Fe)_2SiO_4$, a group of minerals formed from individual silicon–oxygen tetrahedra, with magnesium (Mg) and iron (Fe) substituting for each other in variable amounts from pure magnesium to pure iron; *pyroxene*, $(Ca, Mg, Fe)_2Si_2O_6$, a single-chain silicon–oxygen tetrahedra group of minerals; and *amphibole*, $(Na, Ca)_2(Mg,Al, Fe)_5Si_8O_{22}(OH)_2$, a double-chain silicon–oxygen tetrahedra group of minerals.

Because they are not very resistant to weathering and erosional processes, ferromagnesian minerals tend to be altered or removed from their location relatively quickly. They weather readily and combine with oxygen during the chemical process known as *oxidation*. Oxides are mineral compounds that link oxygen with metallic elements, as, for example, hematite and limonite (hydrous iron oxide, common rust). Ferromagnesian minerals combine readily with other elements to form clays and soluble salts. Ferromagnesian minerals, when abundant, may produce weak rocks, and builders must be cautious when evaluating a construction site that contains rocks high in ferromagnesian minerals. Caution is especially important for highway, tunnel, and reservoir planning.

Other Important Rock-Forming Minerals

Oxides. Earth materials containing useful minerals, especially metals, that can be extracted at a profit are called *ores* (discussed further in Chapter 15). Iron and aluminum, probably the most important metals in our industrial society, are extracted from ores containing iron and aluminum oxides. The most important iron ore is hematite (an iron oxide, Fe_2O_3), and the most important aluminum ore is bauxite (a mixture of several aluminum oxides). Magnetite (Fe_3O_4, also an iron oxide, but economically less important than hematite) is common in many rocks. Magnetite, also known as lodestone, is a natural magnet that attracts and holds iron particles. Where particles of magnetite or other dark minerals are abundant, they may produce layers of black sand in streams or beach deposits.

Carbonate Minerals. Environmentally, the most important *carbonate mineral* is calcite (calcium carbonate, $CaCO_3$), shown in Figure 3.7e. This mineral is the major constituent of limestone and marble, two very important rock types. Many marine organisms, from oysters and clams to forminifera (discussed

FIGURE 3.11 Limestone caverns Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico. Spelunker (person exploring cave) Neeld Messler is working his way down into the cave. *(Michael Nichols/National Geographic Image Collection)*

FIGURE 3.12 Acid mine drainage This stream in Jackson County, Ohio, is polluted by acid mine drainage from a strip mine. *(Matt Meadows/Peter Arnold, Inc.)*

earlier, with oxygen isotopes), have shells composed of carbonate minerals. Chemical weathering of such rocks by water dissolves the calcite, often producing caverns, sinkholes, or surface pits (**Figure 3.11**).

Sulfide Minerals. Pyrite (iron sulfide, FeS_2), also known as fool's gold, is a *sulfide mineral* and is shown in Figure 3.7f. Sulfides can also be associated with environmental degradation, which typically occurs when roads, tunnels, or mines cut through coal-bearing rocks that contain sulfide minerals. The exposed sulfides oxidize, or combine with oxygen, in the presence of water to form compounds, such as sulfuric acid, that may enter and pollute streams and other environments (**Figure 3.12**). This is a major problem in the coal regions of Appalachia and many other regions of the world where sulfur-rich coal and sulfide minerals are mined (see Chapter 16).

Native Elements. Minerals formed of a single element are called *native elements*; gold, silver, copper (Figure 3.7g), and diamonds are examples of native elements. They have long been sought as valuable minerals. They occur in rather small accumulations but are occasionally found in sufficient quantities to justify mining. As we mine these minerals in ever lower-grade deposits, the environmental impact will increase because the larger the mine, the greater the environmental impact. (The environmental effects of mining are discussed in Chapter 15.)

3.3 Rock Cycle

What Is a Rock? A **rock** is an aggregate of one or more minerals. That is, some rocks are formed from a single mineral, and others are composed of several minerals. Although rocks vary greatly in their composition and properties, they can be classified into three general types, or families, according to their mineralogy—or mineral composition, chemical composition, and *texture* (size, shape, and arrangement of grains) (see Appendix B)—and how they were formed during the **rock cycle** (**Figure 3.13**). We can consider this cycle a worldwide rock-recycling system linking subsurface processes driven by Earth's internal heat, which melts or changes rocks in the tectonic cycle, to surface processes driven by solar energy. The rock cycle produces three general families of rock: igneous rocks, sedimentary rocks, and metamorphic rocks. Crystallization of molten rock produces *igneous rocks* both beneath and on Earth's surface. Rocks at or near the surface break down chemically and physically by weathering, forming sediments that are transported by wind, water, and ice to depositional basins, such as the ocean (see A Closer Look: Weathering). The accumulated layers of sediment eventually undergo

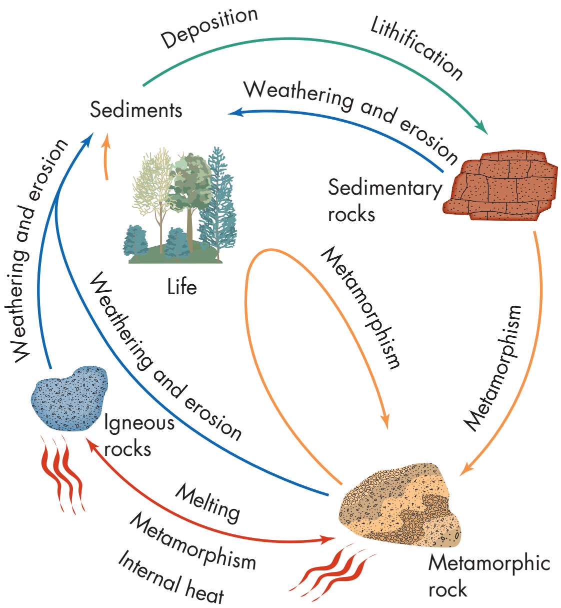


FIGURE 3.13 The rock cycle Idealized rock cycle showing the three families of rocks and important processes that form them. Life is part of the cycle, adding carbon and other elements to sediments that contribute to sedimentary rocks including coal and other fossil fuels. Linkages between life and geology are discussed in Chapter 4.

chemical and physical changes, forming *sedimentary rocks*. Deeply buried sedimentary rocks may be metamorphosed, or altered in form by heat, pressure, or chemically active fluids, to produce *metamorphic rocks*. Metamorphic rocks may be buried still more deeply and melt, beginning the cycle again. Some variations of this idealized sequence are shown in Figure 3.13. For example, an igneous or metamorphic rock may be altered into a new metamorphic rock without undergoing weathering or erosion. To summarize, the type of rock formed in the rock cycle depends on the rock's environment.

Rock Cycle and Plate Tectonics

Plate tectonics provides several environments for rock formation, with specific rock-forming processes occurring at each type of plate boundary (**Figure 3.14**). When we consider the rock cycle alone, we are concerned mainly with the recycling of rock and mineral materials. However, the tectonic processes that drive and maintain the rock cycle are essential in determining the properties of the resulting rocks. Therefore, our interest in plate tectonics is more

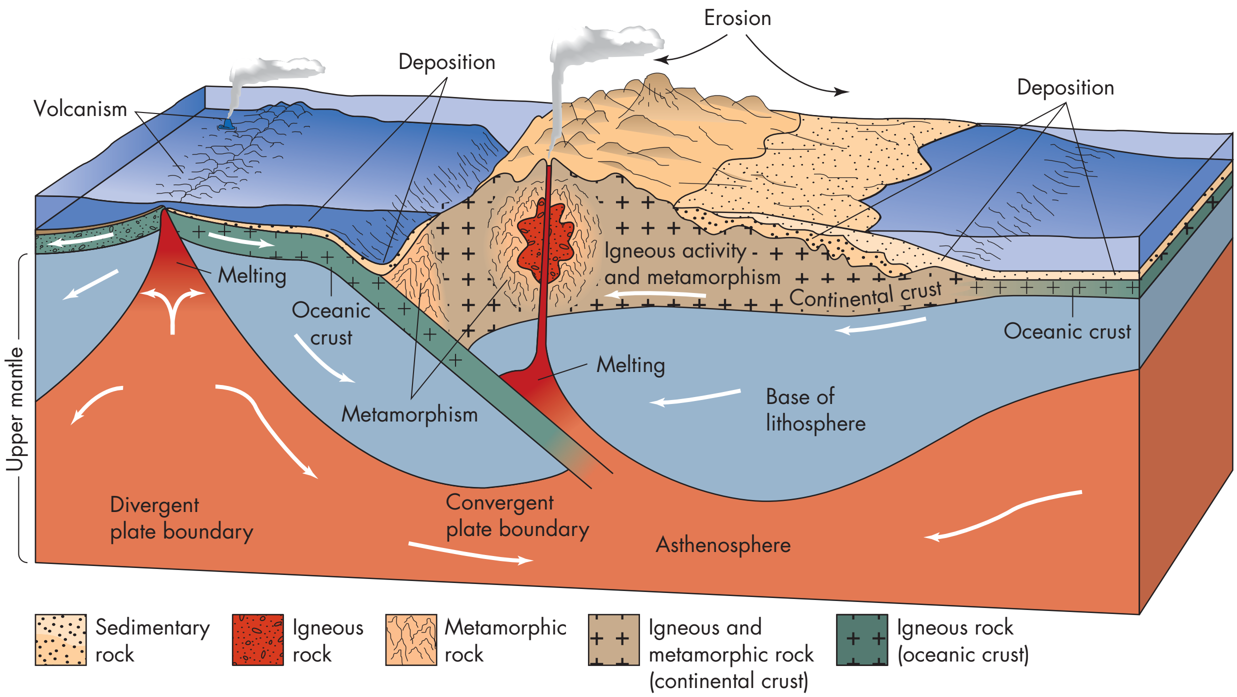


FIGURE 3.14 Rock environments Idealized diagram showing some of the environments in which sedimentary, igneous, and metamorphic rocks form. *(Modified after Judson, S., Kauffman, M. E., and Leet, L. D. 1987.* Physical Geology, *7th ed. Englewood Cliffs, NJ: Prentice Hall)*

than academic; we build our homes, industries, and roads and grow our crops on these Earth materials.

3.4 Three Rock Laws

Understanding Earth history through geologic time requires knowing some fundamental laws. Three of the most important are:

1. The **law of crosscutting relationships**, which states that a rock is younger than any other rock that it cuts.
2. The **law of original horizontality**, which states that when originally deposited, sedimentary layers are nearly horizontal.
3. The **law of superposition**, which states that if a series of layered sediments have not been overturned, the oldest layers are on the bottom and the youngest are on top.

We will return to these laws in our discussion of rocks, their geologic history, and their environmental significance. We will begin our discussion with igneous rocks and then will consider sedimentary rocks and metamorphic rocks.

3.5 Igneous Rocks

Igneous rocks have crystallized from *magma*, a mobile mass of hot, quasi-liquid Earth material consisting of a mixture of melted and solid materials. Magma is often generated in the upper asthenosphere or the lithosphere (Figure 3.14). You can visualize magma as hot, slushy, cherry pie filling consisting of the filling liquid mixed with solid cherries.

Intrusive Igneous Rocks

If magma cools slowly and crystallizes well below the surface of Earth, the result is *intrusive* igneous rock. Individual mineral grains can be seen with the naked eye. Crystals in intrusive igneous rocks that are larger than the surrounding crystals, well formed, and surrounded by relatively finer-grained crystals are known as *phenocrysts*. When intrusive igneous rocks are exposed on Earth's surface, we can assume that erosion has removed the surface material originally covering them. As the molten magma rises toward the surface, it displaces the rock it intrudes, often breaking off portions of the intruded rock and incorporating them as it crystallizes. These foreign blocks, known as *inclusions*, are evidence of forcible intrusion.

Common types of intrusive igneous rocks, such as granite, granodiorite, diorite, and gabbro, and their general mineralogy, are shown in **Figure 3.15**. For example, granite is composed mostly of potassium-rich alkali feldspar and quartz, with minor amounts of sodium-rich feldspar, the micas muscovite and biotite, and amphibole (**Figure 3.16a**).

Batholiths and Plutons

Magma that forms a body of intrusive igneous rock emplaced in the crust in a particular region may be truly gigantic, often exceeding thousands

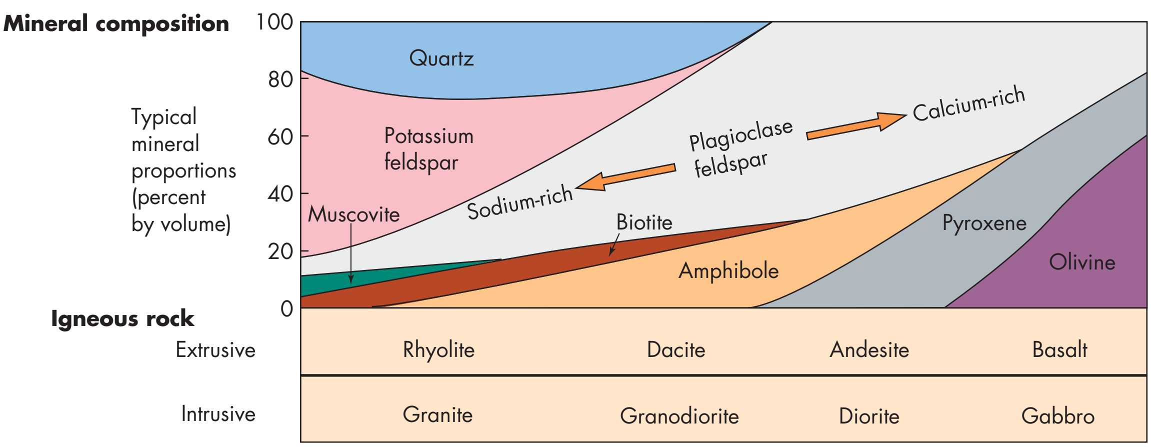


FIGURE 3.15 Igneous rocks Types of extrusive and intrusive igneous rocks and their characteristic mineral composition. Note that every extrusive rock has an intrusive counterpart. For example, rhyolite and granite are composed of the same minerals, but rhyolite cooled at the surface of Earth, whereas granite cooled beneath the surface of Earth. *(Modified after Davidson, J. P., Reed, W. E., and Davis, P. M. 1997.* Exploring Earth. *Upper Saddle River, NJ: Prentice Hall)*

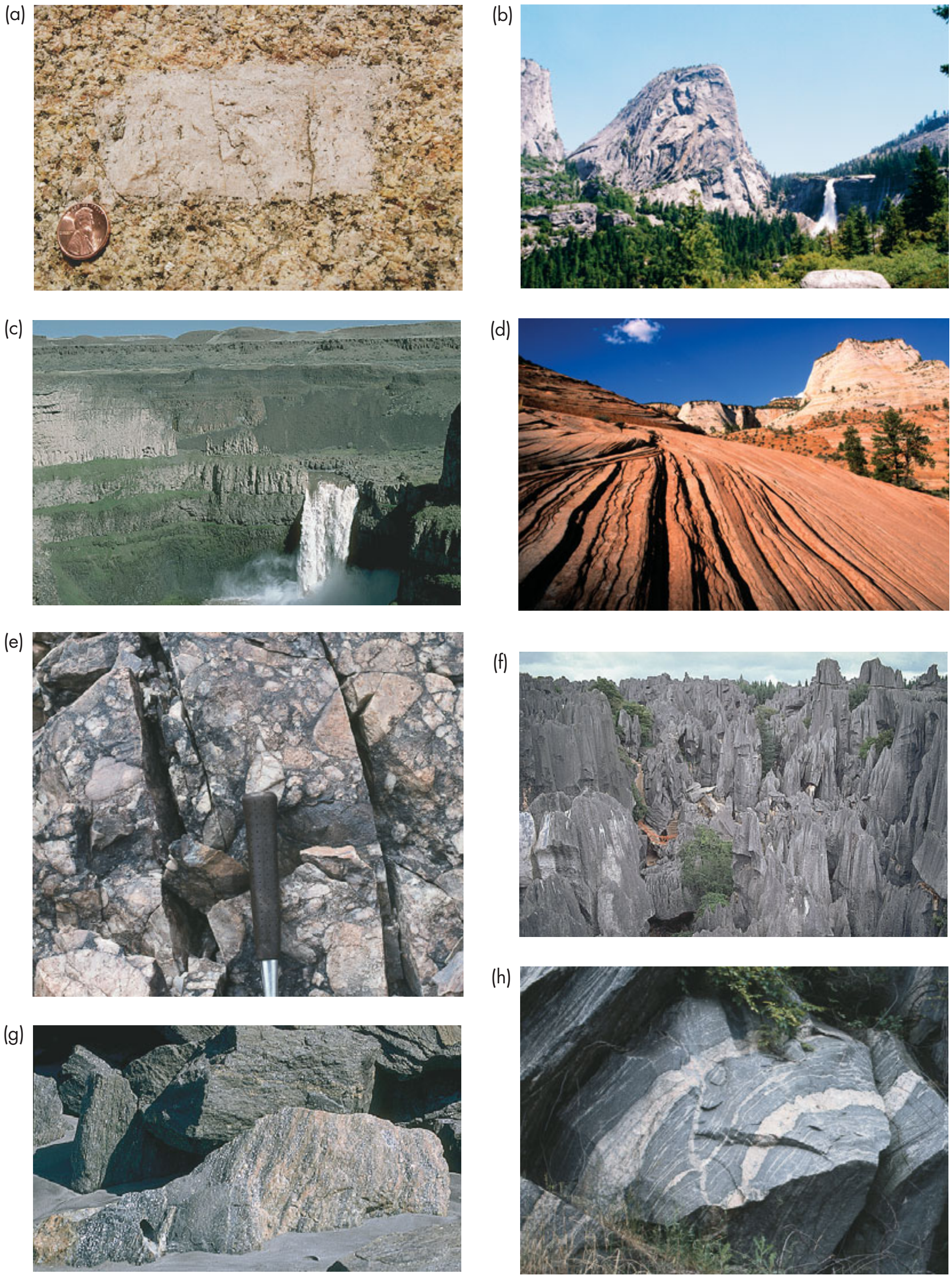


FIGURE 3.16 Some common rock types (a) A specimen of granite. The pink fine-grained mineral is feldspar, the dark mineral is ferromagnesian, and the very light-colored mineral is quartz. The large crystal in the center is known as a phenocryst, which is a coarse crystal in a finer matrix of other crystals. The phenocryst in this case is feldspar. *(Betty Crowell/Faraway Places)* (b) Granite dome in Yosemite Valley, California. *(Edward A. Keller)* (c) Layered rocks here are basalt flows along the Palouse River in Washington. *(Betty Crowell/Faraway Places)* (d) Rocks exposed here in the foreground are sandstone. The parent material was a sand dune that has been cemented and turned to stone, Zion National Park, Utah. *(Guiziou Franck/Photolibrary)* (e) The rock shown here is a conglomerate found in Death Valley, California. Individual particles that are cemented together are easily seen; the vertical lines are fractures in the rock. *(Betty Crowell/Faraway Places)* (f) The rock exposed here is a highly weathered limestone in the Yunnan Province of China. The pinnacles are formed by chemical weathering of the limestone and removal of cover soil material. *(Betty Crowell/Faraway Places)* (g) Schist, a foliated metamorphic rock in which parallel alignment of mineral grains, in this case mica, produces the foliation and reflects the light. *(Marvin B. Winter/Photo Researchers, Inc.)* (h) Gneiss, a foliated metamorphic rock with minerals segregated into white bands of feldspar and dark bands of ferromagnesian minerals. *(John Buitenkant/Photo Researchers, Inc.)*

of cubic kilometers. The largest intrusions are called *batholiths*, which are composed of a series of smaller intrusions known as plutons. *Plutons* are variable in size but may be as small as a few kilometers in width. Some intrusions, such as dikes and sills, are tabular in form, relatively long and narrow (**Figure 3.17**). Dikes intrude through and cut across existing rocks, whereas sills intrude parallel to the rock layers. Most dikes we observe in the field are relatively small, less than 1 m to a few meters in width. Dikes can form complex patterns that either cut across one another or are in a radial pattern; these patterns are known as *dike swarms*. Most batholiths are formed of granitic rocks, but dikes and sills may be basaltic. Sometimes it is possible to distinguish younger from older plutons by examining them in the field where they are exposed by erosion. For example, the light gray pluton in Figure 3.17 contains inclusions, or pieces of the dark gray pluton, within it. Inclusions allow geologists to determine the relative ages of the plutons. A pluton that contains inclusions of another pluton within it must be the younger of the two.

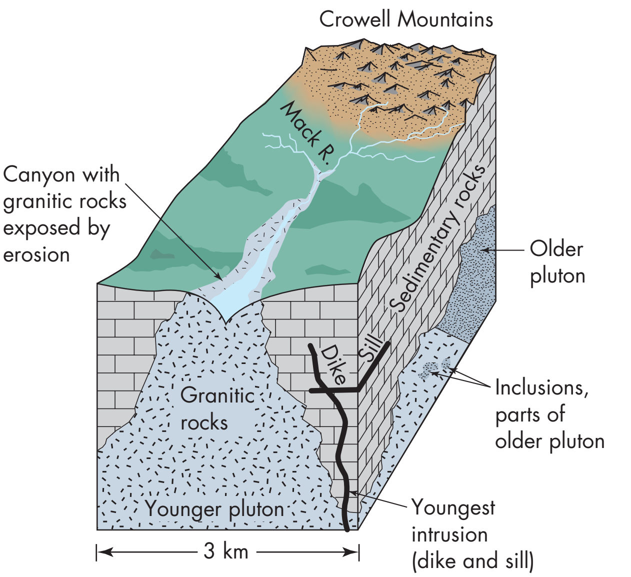


FIGURE 3.17 Igneous intrusions Idealized block diagram showing several types of igneous intrusions. The older pluton is known to be older; it is cut by the younger pluton, and inclusions of the older pluton are found in the younger. The youngest intrusions in the diagram are the dike and sill. Notice that the younger pluton is exposed at the surface in a canyon similar to the exposure of granitic rocks in Yosemite shown in Figure 3.16b. Assuming that the pluton was emplaced at a depth of more than 10 km (about 6.2 mi), one finds an appreciation for the tremendous amount of erosion necessary to expose granitic rocks in canyons such as Yosemite Valley.

Therefore, the light gray pluton is younger than the dark gray pluton. The youngest intrusion in Figure 3.17 is the dike and sill that cuts across the younger pluton. This analysis demonstrates the *law of cross-cutting relationships*, which states that a rock is younger than any other rock that it cuts.

Why Magma Rises and Intrudes Other Rocks

One commonly asked question is, "Why do masses of partially melted rock or magma rise or intrude the surrounding rocks?" A probable explanation is that once the internal heat of Earth has formed a mass of magma, it is hotter and less dense than the surrounding rocks and, therefore, rises much as a helium-filled balloon rises in the atmosphere or as a scuba diver's air bubbles rise through the water. Presumably, once the density differences are equalized, the mass of magma or intrusion ceases its upward journey toward the surface of Earth, and the magma completes the crystallization of minerals to form intrusive igneous rocks. Often, before crystallization to form intrusive igneous rocks occurs, however, some magma reaches the surface of Earth to cause volcanic eruptions and form extrusive igneous rocks.

Extrusive Igneous Rocks

Igneous rocks that crystallize at the surface of Earth are called *extrusive*. Extrusive igneous rocks often form from lava, or molten magma flowing from volcanoes. They can also form from pyroclastic debris, composed of fragmented magma that has rapidly solidified as it was blown out of a volcano.

Extrusive igneous rocks are fine-grained due to rapid cooling and crystallization, and individual crystals or grains usually cannot be seen with the naked eye. However, extrusive igneous rocks may have previously formed phenocrysts of minerals that crystallized when the magma was deeper within Earth, and crystallization was slower. The texture of such a rock, which has relatively few, often well-formed, phenocrysts surrounded by a mass of fine-grained crystals, is called *porphyritic*. There are different types of extrusive igneous rock, such as rhyolite, dacite, andesite, and basalt, just as there are different types of intrusive igneous rock (Figure 3.15). The specific type is based on differences

in the rocks' chemical composition. Notice in Figure 3.15 that the minerals in rhyolite are the same as in granite, as is the case with dacite and granodiorite, andesite and diorite, and basalt and gabbro. It is the size of the crystals formed by the process of crystallization, either at the surface or deep beneath the surface of Earth, that differentiates extrusive from intrusive igneous rocks. We often identify intrusive igneous rocks from hand specimens by examining the phenocrysts present. For example, andesite may have phenocrysts of feldspar (**Figure 3.18**), whereas basalt is more likely to have phenocrysts of pyroxene or olivine. We will discuss extrusive rocks and their differences in more detail in Chapter 8 when we discuss volcanoes.

Extrusive rocks form from lava or magma that crystallizes at the surface. A lava flow may be mixed with cemented fragments of broken lava and ash, called *volcanic breccia*, or with thick vesicular, or cavity-filled, zones produced as gas escapes from cooling lava.

Pyroclastic debris, also known as tephra, ejected from a volcano produces a variety of extrusive rocks (**Figure 3.19**). Debris consisting of rock and glass fragments less than 4 mm (about 0.16 in.) in diameter are called *volcanic ash*; when this ash is compacted, cemented, or welded together, it is called *tuff*. Pyroclastic activity also produces larger fragments that, when mixed with ash and cemented together, form the rock called *volcanic breccia*.

Extrusive igneous rocks may develop into piles of layered volcanic rocks surrounding volcanoes that form entire islands, such as the Hawaiian Islands in the Pacific. They may also form basaltic plateaus that cover many thousands of square kilometers with a series of basaltic flows of great thickness (see Figure 3.16c, part of the Snake River Basaltic Plateau in Washington).

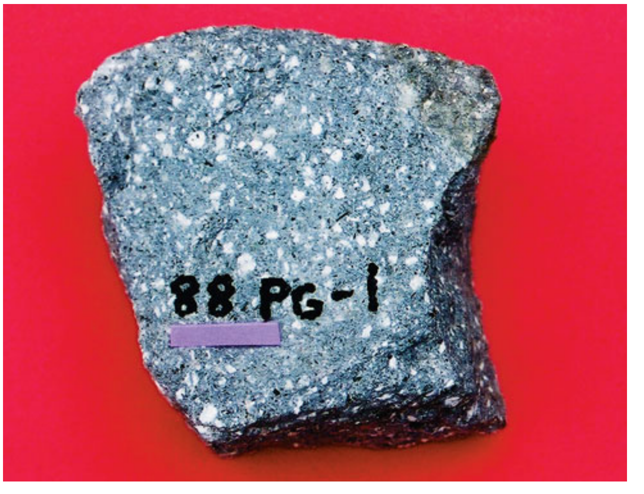


FIGURE 3.18 Andesite Hand specimen of andesite with white feldspar phenocrysts. Bar is 2.5 cm (1 in.). *(Edward A. Keller)*

FIGURE 3.19 Pyroclastic debris Pyroclastic deposits, fine-grained volcanic ash, pumice (light-colored layers), and coarser pyroclastic fragments (marble sized) mixed with ash; north flank of Tenerife, Canary Islands. *(Edward A. Keller)*

FIGURE 3.20 Columnar jointing or fracturing These joints or fractures in basalt form because of contraction during cooling. This photo was taken at Devil's Postpile National Monument, Sierra Nevada, California. *(A. G. Sylvester)*

Igneous Rocks and the Environment

Intrusive and extrusive igneous rocks have a wide variety of properties, and generalizations are difficult. We can, however, make three environmental points associated with these rocks:

- Intrusive igneous rocks, especially granite, are generally strong rocks that make a good foundation for many structures, such as dams and large buildings. Blocks of these rocks are often resistant to weathering and are used for a variety of construction purposes.[6,7]
- Lava flows that have cooled and solidified often exhibit extensive *columnar jointing* (**Figure 3.20**). Columnar jointing is a type of fracturing that occurs during cooling that may lower the strength of the rock. Solidified lava flows may also have subterranean voids known as lava tubes. Lava tubes can collapse from the weight of the overlying material or can carry large amounts of groundwater. Both features can cause problems during the planning, design, and construction phases of a project.
- Tuff is generally a soft, weak rock that may have very low strength.[6] The strength of a tuff rock depends upon the degree to which it has become cemented or welded. Some tuff may be altered through weathering into a type of clay known as *bentonite*, an extremely unstable material. When bentonite is wet, it expands to many times its original volume and is unstable.

It is difficult to make generalizations about the suitability of extrusive igneous rocks for specific uses. Careful field examination is always necessary before large structures are built on such rocks.[6] Planning, designing, and constructing engineering projects on extrusive rocks, especially pyroclastic debris, can be complicated and risky.[7] This fact was tragically emphasized on June 5, 1976, when the Teton Dam in Idaho failed, killing 14 people and inflicting approximately $1 billion in property damage. Just before the failure, a whirlpool several meters across was seen in the reservoir, strongly suggesting that a tunnel of free-flowing water had developed beneath the dam. In fact, the dam was built upon highly fractured volcanic rocks. Water began moving under the foundation as the reservoir filled. When the subsurface moving water came into contact with the dam, it quickly eroded a tunnel through the base of the dam, causing the whirlpool. The dam collapsed just minutes later, and a wall of water up to 20 m (66 ft) high rushed downstream, destroying homes, farms, equipment, animals, and crops for 160 km (100 mi) downstream from the dam failure.

3.6 Sedimentary Rocks

Sedimentary rocks constitute about 75 percent of all rocks exposed at the surface of Earth (**Figure 3.21**). Their common environments are shown in Figure 3.14. There are two types of sedimentary rock: *detrital*, or clastic, sedimentary rocks, which form from broken parts of previously existing rocks; and *chemical*, or nonclastic, sedimentary rocks, which are deposited when chemical or biochemical processes cause minerals to form from substances dissolved in water.

Sedimentary rocks form when sediments are transported, deposited, and then transformed into rock, by natural cementation or compaction or both.

FIGURE 3.21 Sequence of sedimentary rock The Grand Canyon of the Colorado River exposes a spectacular section of sedimentary rocks. The top sedimentary unit is the Kaibab limestone, below which is a series of sandstones, shales, and the famous Red Wall limestone. *(Hal Gage/Photolibrary)*

After deposition, both physical and chemical changes in sediments occur in response to increased pressure and temperature. The increase in pressure and temperature is not sufficient to produce metamorphic rocks. These changes in the sediments are a result of their being buried and of fluids migrating through them. These processes are collectively referred to as *diagenesis*. Some of these processes are shown in idealized form in Figure 3.22:

- Sediment from a river is delivered to a sedimentary basin—in this case, an ocean. The basin is only one of many types of *sedimentary environments* on Earth. Other sedimentary environments include lakes, river floodplains, sand dunes, and glacial environments.
- As the river enters the ocean at point A, the coarser sediment (sand) is deposited first at point B, and finer silt and clay are deposited farther from the shoreline where the transport processes are weakest, at point C. The sediment is deposited in beds, or layers.

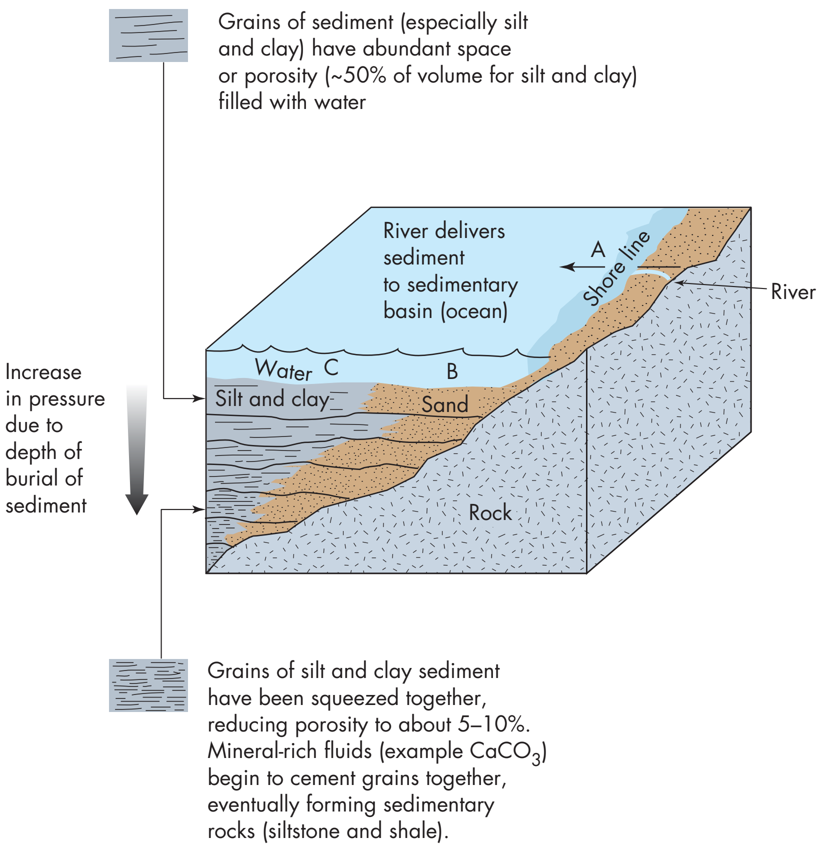


FIGURE 3.22 Diagenesis Idealized block diagram illustrating some of the processes of diagenesis that transform sediments into sedimentary rocks. Points A, B, and C correspond to locations discussed in the text.

FIGURE 3.23 Tilted sedimentary rocks Lines generally running from lower left to upper right are bedding planes of these sedimentary rocks. The layers are inclined about 30 degrees. The law of original horizontality states that these bedding planes were close to horizontal when the sediment grains forming the rocks were deposited. We assume that they are at 30 degrees today because they have been uplifted and tilted by tectonic processes. *(Edward A. Keller)*

Individual beds are nearly horizontal when deposited, as stated in the *law of original horizontality*. The sequences of beds are known as *strata*. The top bed, and others, may have been produced by a single large flood event from the river. The different layers are separated by *bedding planes* (**Figure 3.23**) that denote the top and bottom of a particular sedimentary bed. The layering of sedimentary rocks, therefore, results from changes in deposition associated with grain size, difference in composition of the sediments, or a series of events, such as large floods that periodically bring a greater amount of sediment into the sedimentary basin. A particular sedimentary bed may change or grade laterally from one type of sediment to another—for example, the sand, silt, and clay illustrated in Figure 3.22. The lateral change in sediment is referred to as a *facies* change; in this case, a sandy facies has changed into a silt and clay facies in the same sedimentary unit.

- As the sedimentary basin sinks or sea level rises, sediments (strata) up to several kilometers in thickness may be deposited. Recall the spectacular section of sedimentary rocks in the Grand Canyon shown in Figure 3.21.
- When the sediment was originally deposited, there was open space between the grains. This space between the grains, known as *porosity*, is filled with water; therefore, for each cubic meter (about 35 ft^3) of the sediment, half of the space is occupied by water between the grains. The oldest sedimentary beds are located at the bottom of the sedimentary basin. As stated in the *law of superposition*, if a series of sedimentary beds have not been overturned, the youngest beds are on the top and the oldest on the bottom. The sedimentary deposits near the bottom are subjected to both an increase in pressure due to the weight of the overlying sediments and an increase in temperature resulting from natural heat flow from the interior of Earth. The increase in pressure causes the grains to be squeezed tightly together, forcing out some of the water. The rate at which water is forced out is dependent, in part, on the ease with which the water passes through the pore spaces between the particles. Increased pressure and temperature may facilitate the dissolving of some minerals, forming mineral-rich fluids that migrate through the sediments and begin to cement them. Common cementing materials might be carbonate ($CaCO_3$) or silicon oxide (SiO_2). As these diagenetic processes continue, the sediments are transformed into sedimentary rock. If they are buried deeply enough, diagenesis may proceed to metamorphism, which is discussed in the following section.

Detrital Sedimentary Rocks

Detrital sedimentary rocks are classified according to their grain size as either shale, siltstone, sandstone, or conglomerate (**Table 3.3A**). Shale and siltstone, along with poorly bedded mudstone and claystone, are by far the most abundant detrital rocks, accounting for about 50 percent of all sedimentary rocks. Composed of clay- and silt-sized particles, they are the finest grained of the four detrital rock types. Remember that we defined clay in terms of its

TABLE 3.3 Detrital (A) and Chemical (B) Sedimentary Rocks

	Size	Sediment	Rock
(A) Detrital (Clastic) Sedimentary Rocks	Greater than 2 mm	Gravel	**Conglomerate:** often has a sandy matrix. If particles are angular, rock is called breccia (Figure 3.17d).
	$\frac{1}{16} - 2$ mm	Sand	**Sandstone:** generally designated as coarse (0.5–1 mm), medium (0.25–0.49 mm), or fine (0.13–0.24 mm) if well-sorted (consisting of sand particles of approximately the same size). Have also been subdivided on the basis of the composition; the more important types are: **Quartzose sandstone** (mainly quartz; see Figure 3.17c) **Arkosic sandstone** (arkose): over 20 percent feldspar **Graywacke:** poorly sorted (consisting of sand particles of many sizes mixed together); contains rock fragments with a clay matrix
	$\frac{1}{256} - \frac{1}{16}$ mm	Silt	**Siltstone** (mudstone): compacted or cemented silt and clay lacking fine lamination
	Less than $\frac{1}{256}$ mm	Clay	**Shale:** compacted or cemented silt and/or clay with fine laminations along which rock easily splits (fissility). Rocks composed of clay that lack fissility are called claystone. Mudstone is an unlaminated mixture of silt and clay.
	Principal Composition	**Principal Texture**	**Rock**
(B) Chemical (Nonclastic) Sedimentary Rocks	Calcite, $CaCO_3$	Fine[1]	**Limestone:** often of biologic origin and may contain fossils. *Coquina* is limestone composed mainly of fossils or fossil fragments. Effervesces in diluted hydrochloric acid.
	Calcite, $CaCO_3$	Fine	**Chalk:** soft, white limestone formed by the accumulation of microscopic shells. Effervesces with dilute hydrochloric acid.
	Silica, SiO_2	Fine	**Chert:** hardness 6 or 7,[3] often white, flint is black or dark gray.
	Gypsum, $CaSO_4 \cdot 2H_2O$	Fine to coarse[2]	**Gypsum:** hardness 2. One good cleavage and two poorer cleavages.
	Halite, NaCl	Fine to coarse	**Rock salt:** cubic crystals and cleavage may be visible. Salty taste.
	Silica, SiO_2	Fine	**Diatomite:** soft, white rock formed by the accumulation of microscopic shells composed of silica. Distinguished from chalk by lack of effervescence in diluted hydrochloric acid.

[1]Cannot see grains with naked eye; generally grain size is less than 1/16 mm.

[2]Can see grains with naked eye; generally grain size is greater than 2 mm.

[3]See Appendix A for definition of hardness.

Modified after Foster, R. J. 1991. Geology, *6th ed. Upper Saddle River, NJ: Prentice Hall.*

mineral composition (see A Closer Look: Clay) and stated that geologists also use the term in a textural sense to mean very fine-grained sediment (less than 1/256 mm in diameter).

When layers of clay or silt (slightly coarser-grained sediment, 1/256 to 1/16 millimeters in diameter) are compacted or cemented, they form shale or siltstone. Siltstone is more massive, generally lacking bedding planes, whereas shale characteristically has closely spaced bedding planes.

Sandstone and *conglomerate* are coarser grained than shale and siltstone and make up about 25

percent of all sedimentary rock (Figure 3.16d,e). Sand-sized particles of sandstone are 1/16 to 2 mm in diameter. Conglomerate contains gravel-sized particles greater than 2 mm in diameter, cemented together with material such as silica, calcium carbonate, iron oxide, or clay.

Chemical Sedimentary Rocks

Chemical sedimentary rocks are classified according to their mineral composition; they include halite (rock salt, NaCl); gypsum (hydrated calcium sulfate, which is calcium sulfate containing water, $CaSO_4 \cdot 2H_2O$); and limestone, which is composed mostly of the mineral calcite (calcium carbonate, $CaCO_3$) (Table 3.3B) (Figure 3.16f). Limestones make up about 25 percent of all sedimentary rocks and are by far the most abundant of the chemical sedimentary rocks.

Sedimentary Rocks and the Environment

Three primary environmental concerns associated with sedimentary rocks are as follows:

- Shale, mudstone, and siltstone are often very weak rocks. They may cause many environmental problems, and their presence is a red flag to the applied Earth scientist. However, some shale can be a very stable, strong rock, suitable for many construction purposes, depending on the degree of cementation and type of cementing material. In general, the presence of any shale, mudstone, or siltstone at a building site requires a detailed evaluation to determine the physical properties of the rock.
- Limestone is not always well suited for human use and activity. Although this rock may be strong enough to support construction, it easily weathers to form subsurface cavern systems and solution pits on the surface caused by chemical weathering. Solution pits are also known as sinkholes (see Chapter 13). Constructing highways, reservoirs, and other structures is problematic in areas where caverns or sinkholes are encountered. Another problem common in limestone areas is that subsurface water in cavern systems may quickly become polluted by urban runoff, with little or no chance of natural purification of the polluted water.
- Cementing materials in detrital sedimentary rocks may be troublesome. Silica cement is the strongest; calcium carbonate tends to dissolve in weak acid; and clay may be unstable and wash away. It is always advisable to carefully evaluate the strength and stability of cementing materials in detrital sedimentary rocks.

3.7 Metamorphic Rocks

Igneous and metamorphic rocks together account for more than 90 percent of all rocks in Earth's crust. **Metamorphic rocks** are changed rocks; that is, heat, pressure, and chemically active fluids produced by the tectonic cycle or resulting from the presence of an intrusion may change the mineralogy and texture of preexisting rocks, in effect producing new rocks. Generalized geologic environments along with pressure–temperature conditions that result in metamorphism are idealized in **Figure 3.24**. The three major types of metamorphism are:

1. High-pressure, low-temperature metamorphism; characteristic of subduction zones.
2. High-temperature, high-pressure metamorphism; characteristic of *regional metamorphism* that might be produced during continental collision. Notice that in this environment, rock metamorphism changes low-grade sedimentary rocks to high-grade metamorphic rocks with increasing temperature and pressure. The rocks progressively change from sedimentary rock to low-grade metamorphic rock known as slate, to an intermediate-grade metamorphic rock known as schist, and finally to a high-grade metamorphic rock known as gneiss. The original shale, a sedimentary rock, is thus transformed to slate, and then schist, and then gneiss, through progressive regional metamorphism as a result of increasing temperature and pressure.
3. High-temperature, low-pressure metamorphism, or *contact metamorphism*. When magma intrudes the upper crust, it heats nearby surrounding rocks, but, because it is close to the surface, the pressure is relatively low. This increased temperature causes the formation of particular types of metamorphic minerals and rocks in the contact zone.

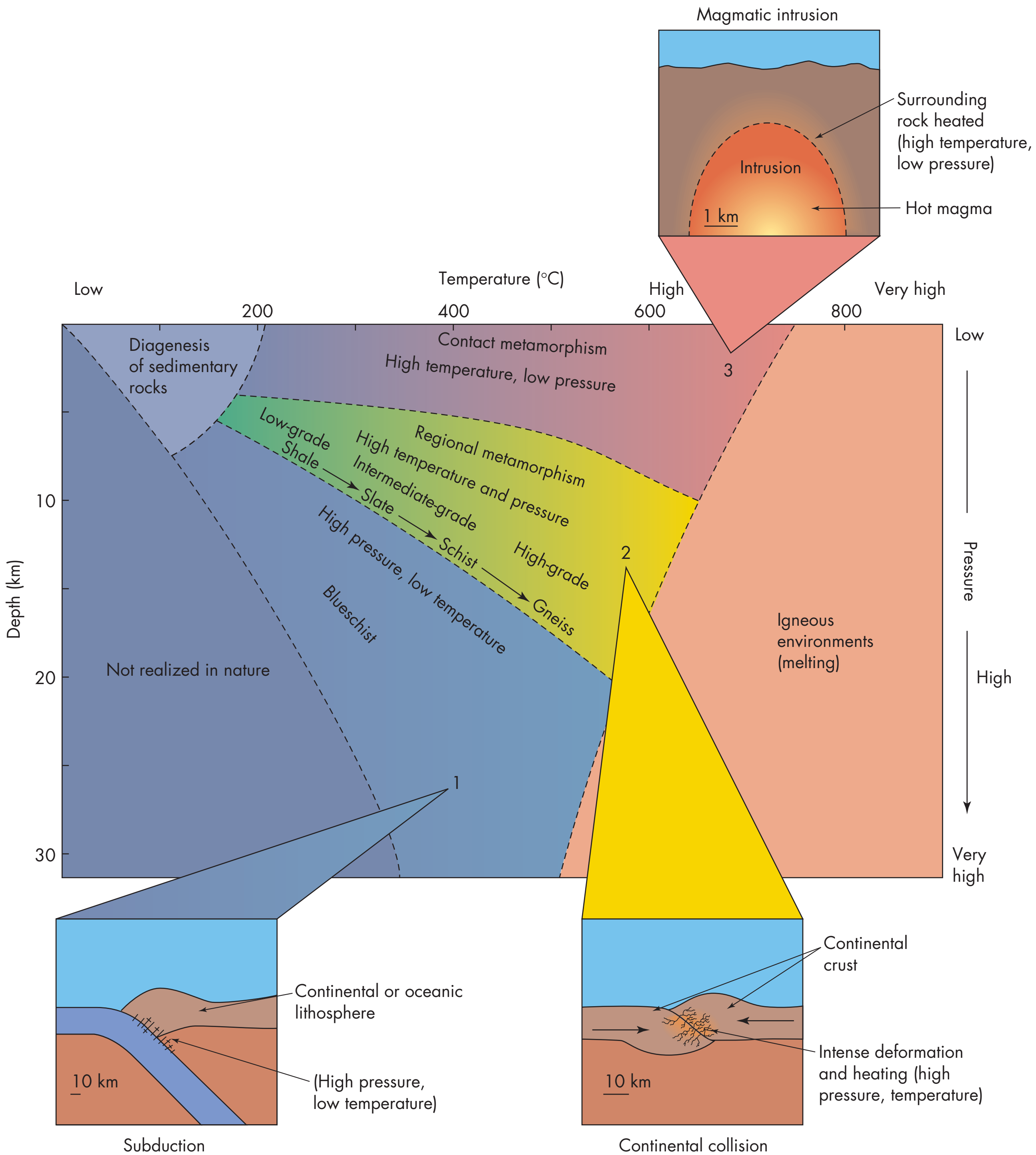


FIGURE 3.24 Geologic environments of metamorphism Highly idealized diagram showing temperature and pressure conditions for diagenesis of sediments and the main types of metamorphism resulting from different pressure–temperature conditions and geologic environments. Subduction zones are characterized by high-pressure metamorphism (1) in which pressure increases as the oceanic lithosphere, with its load of marine sediments, is subducted. Regional metamorphism (2) results from intense deformation, with high temperatures and pressures resulting from continental collisions. Rocks surrounding a body of cooling magma (3) experience high-temperature contact metamorphism at relatively low pressure. *(Modified after Davidson, J. P., Reed, W. E., and Davis, P. M. 1997.* Exploring Earth. *Upper Saddle River, NJ: Prentice Hall)*

Foliated Metamorphic Rocks

Slate is a relatively low-grade metamorphic rock resulting from the metamorphism of the sedimentary rock shale, as shown in **Figure 3.25** and outlined in **Table 3.4**. As illustrated in Figure 3.25, tectonic stress applied to shale under relatively low temperatures and pressures produces a new rock. *Slate* is referred to as a *foliated* metamorphic rock, in which the mineral grains, such as mica, are aligned either in parallel, layering, or banding structure, producing a rock cleavage, or *foliation*. If the slate is subjected to higher temperatures and pressures, it may change to a higher-grade metamorphic rock known as *schist*. Processes of recrystallization intensify the parallel alignment of mineral grains and crystal size increases, often rendering the crystals relatively easy to identify (Figure 3.16g). If the original shale is subjected to even higher temperatures and pressures, then *gneiss*, with a foliated texture characterized by banding of light and dark minerals, may form (Figure 3.16h).

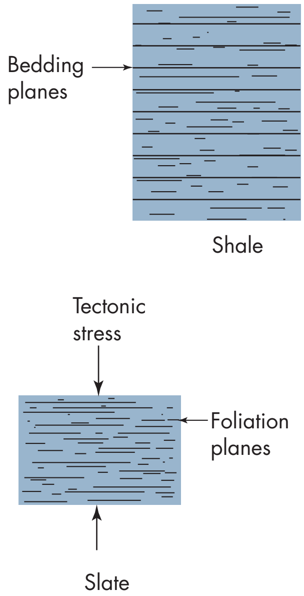


FIGURE 3.25 Transformation of shale to slate Idealized diagram showing the transformation from the sedimentary rock shale to the metamorphic rock slate. The foliation planes in the slate develop as a result of tectonic stress, with recrystallization of the minerals as a result of relatively low-grade metamorphism. Note that the foliation planes form at right angles to the orientation of the tectonic stress (bedding planes are not usually at right angles to the tectonic stress as shown here, but foliation is). In a gross sense, the initial grains in the rock look something like a house of cards. When you place your palm on the house of cards and apply pressure, it collapses and the cards lie flat and stacked on the table, much like the foliation planes in the slate.

Nonfoliated Metamorphic Rocks

Not all metamorphic rocks are foliated. *Marble*, consisting mostly of the mineral calcite ($CaCO_3$), is an example of a nonfoliated metamorphic rock. It results from the metamorphism of limestone, usually due to regional metamorphism or, in some instances, contact metamorphism (**Figure 3.26**). The metamorphic processes cause the calcite to recrystallize into

TABLE 3.4 Metamorphism of Shale

Sedimentary Rock	Low-Grade Metamorphism	Intermediate-Grade Metamorphism	High-Grade Metamorphism
Shale →	Slate →	Schist →	Gneiss
Clay	Very fine clay particles begin to be transformed into very fine-grained mica crystals. Foliation forms.	Mica crystals become large, and rock develops strong foliation.	Mica is transformed mostly to feldspar, producing banding (foliation) of light and dark minerals, such as light feldspar with dark amphibole.
			

FIGURE 3.26 Mountainside view of metamorphic rocks Metamorphic rocks exposed at a mountain range scale, Kejser Franz Joseph Fiord, East Greenland. The east-dipping (center) white unit is marble. This complex exposure is 800 m (2,625 ft) high and includes several normal or extensional faults that merge downward to a very large extensional fault known as a detachment fault. Metamorphic rock types exposed include gneisses as well as the beautiful white marble. *(Ebbe Hartz, University of Oslo)*

larger crystals. If the parent rock is relatively pure limestone, then a beautiful white marble that Michelangelo might have chosen for his work is produced. *Quartzite* is another important nonfoliated metamorphic rock. Quartzite forms from the regional metamorphism of quartz-rich sandstone.

Metamorphic Rocks and the Environment

There are several points to be made concerning metamorphic rocks and the environment:

- *Slate* is generally an excellent foundation material. It has also been used for constructing chalkboards, beds for pool tables, roofing material, and decorative stone counters (**Figure 3.27**). *Schist*, a coarse-grained metamorphic rock, is composed of soft minerals, making it a poor foundation material for large structures (Figure 3.16g). *Gneiss*, a coarse-grained, banded metamorphic rock, is usually a hard, tough rock similar in most respects to granite and suitable for most engineering purposes (Figure 3.16h).
- Foliation planes of metamorphic rocks are potential planes of weakness. The strength of the rock, its potential to slide, and the movement of water through the rock all vary with the orientation of the foliation. Consider, for example, the construction of road cuts and dams in terrain where foliated metamorphic rocks are common. For road cuts in metamorphic rocks, the preferred orientation is parallel to the foliation, or rock cleavage, with planes dipping away from the road cut. Foliation planes inclined toward the road result in unstable blocks that might fall or slide toward the road (**Figure 3.28**). And, since groundwater tends to flow down foliation, foliation planes inclined toward the road would cause a drainage problem. In the construction of dams, the preferred orientation is nearly vertical

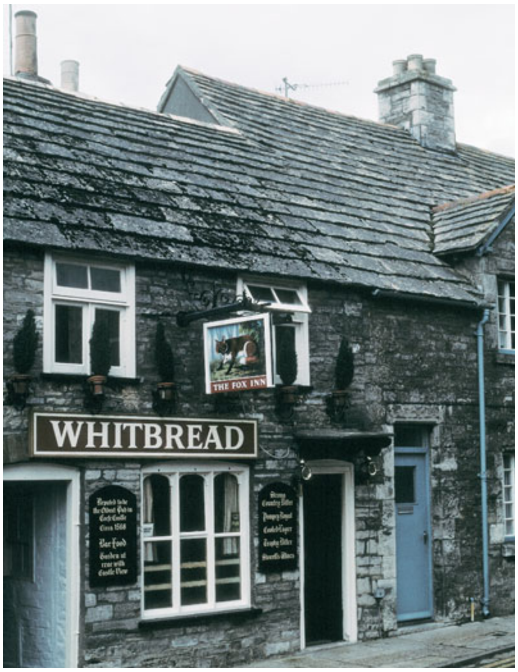


FIGURE 3.27 Slate as roofing material Slate roofs on homes and a pub in southern England. *(Edward A. Keller)*

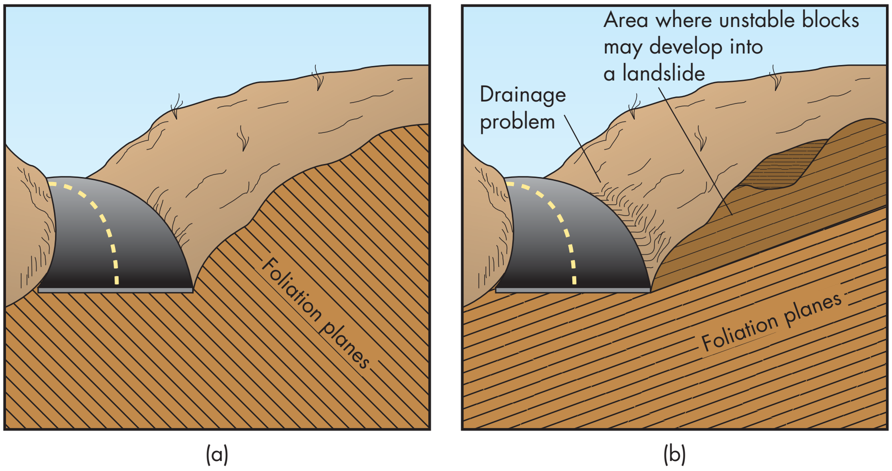


FIGURE 3.28 Foliation and highway stability Two possible orientations of foliation in metamorphic rock and the effect on highway stability. (a) Where the foliation is inclined away from the road, there is less likelihood that unstable blocks will fall on the roadway. (b) Where the foliation is inclined toward the road, unstable blocks of rock above the road may produce a landslide hazard.

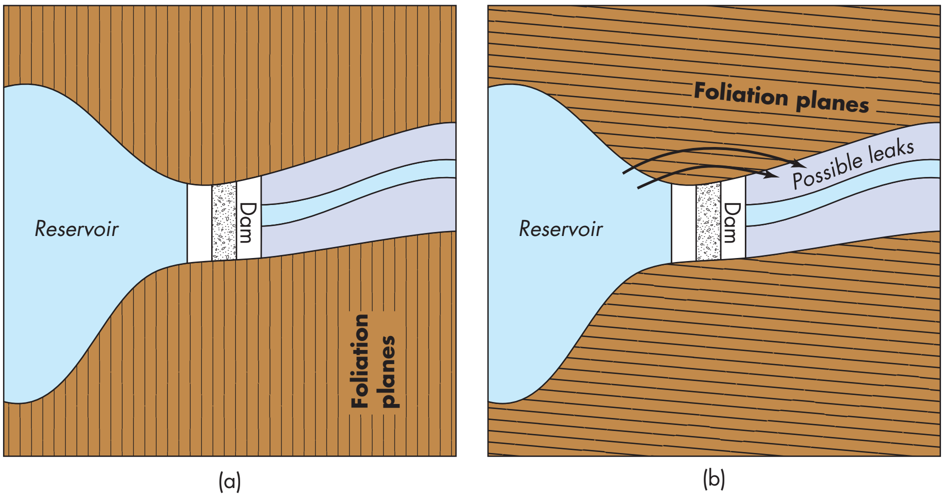


FIGURE 3.29 Foliation and dam stability Two possible orientations of foliation in metamorphic rocks at a dam and reservoir site. (a) The most favorable orientation is for the foliation to be parallel to the axis of the dam. (b) The least favorable orientation is for the foliation planes to be perpendicular to the axis of the dam. This results because water may flow along the foliation, causing water to leak from the reservoir.

foliation planes parallel to the horizontal axis of the structure[6] (Figure 3.29). This position minimizes the chance of leaks and unstable blocks, which are a serious risk when the foliation planes are parallel to the reservoir walls (see Case History: St. Francis Dam).

3.8 Rock Strength and Deformation

The strength of Earth materials, which is generally defined as resistance to failure, such as fracturing, sliding, or flowing, varies with composition, texture, and location. Weak rocks, such as those containing many altered ferromagnesian minerals, may slowly flow under certain conditions and be very difficult to tunnel through. In contrast, some rocks are very strong and need little or no support. However, even strong rocks, when buried deep within Earth, may also flow and be deformed (e.g., rupture, rotation, or change in shape such as shortening, thickening, or thinning). Thus, the strength of a rock may be quite different in different environments.

Deformation of Earth materials may be elastic, plastic, ductile, or brittle. *Elastic* deformation occurs when the deformed material returns to its original shape after the stress is removed. Examples include compressing a rubber ball, stretching a rubber band, and drawing and releasing an archer's bow. *Plastic* deformation, on the other hand, is characterized by permanent change. That is, the material does not return to its original shape after

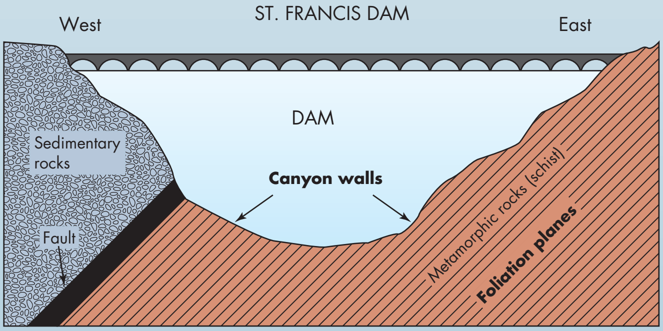
Case History

St. Francis Dam

On the night of March 12, 1928, more than 500 lives were lost and $10 million in property damage was sustained as ravaging floodwaters raced down the San Francisquito Canyon near Saugus, California. The 63 m (207 ft)-high St. Francis Dam, with a main section 214 m (702 ft) long and holding 47 million cubic meters (almost 1.7 billion cubic feet) of water, had failed (**Figure 3.B**).

Why Did the Dam Fail? The causes of the failure were clearly geologic. The east canyon wall was metamorphic rock with foliation planes parallel to the wall. Before the failure, both recent and ancient landslides indicated the instability of the rock. The west wall was sedimentary rock with prominent high topographic ridges that suggested the rock was strong and resistant. Unfortunately, the rocks disintegrated when they became wet. This characteristic was not discovered and tested until after the dam had failed. The contact between the two rock types is a fault with an approximately 1.5 m-thick zone (about 5 ft) of crushed and altered rock. The fault was shown on California's 1922 fault map but either was not recognized or was ignored. Three processes combined to cause the tragedy: slipping of the metamorphic rock, the primary cause of failure; disintegration and sliding of the sedimentary rock; and leakage of water along the fault zone, which washed out the crushed rock. Together, these processes destroyed the bond between the concrete and the rock and precipitated the failure.[7,8] This disaster did serve to focus public attention on the need for geologic investigation as part of siting reservoirs. Such investigations are now standard procedure.

(a)



(b)

FIGURE 3.B Failure of the St. Francis Dam
(a) Before failure. (b) Geology along the axis of the dam. (c) After failure. *(Courtesy of Los Angeles Department of Water and Power)*

(c)

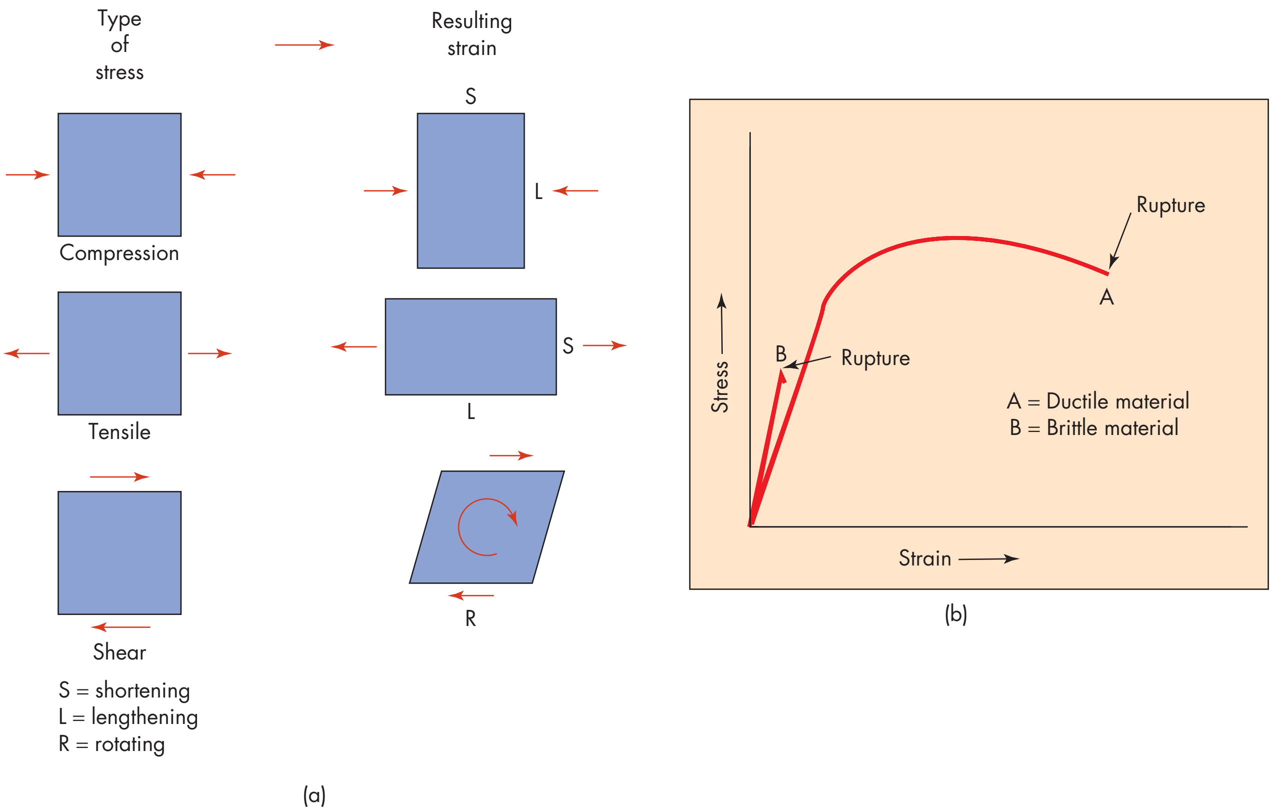


FIGURE 3.30 Stress and strain (a) Types of stress and resulting strain. (b) Relationships between stress and strain in rocks. A brittle rock has no plastic deformation (the curved part of line A).

the stress has been removed. Examples of plastic deformation include compressing snow into a snowball and stretching chewing gum. If a material ruptures before plastic deformation, it is called *brittle*; materials that rupture after considerable plastic deformation are known as *ductile*. The type of deformation that occurs and the rate of deformation depend upon a variety of circumstances, including the type of rock, the magnitude of the stress it is experiencing, how quickly or slowly the stresses are applied, and the temperature of the material. For example, glass at room temperature is hard and behaves like a brittle substance, but glass heated to a high enough temperature is soft and ductile, deforming plastically before rupturing. That is why glassblowers can make such beautiful objects.

The strength of rocks is often recorded as the compressive strength, tensile strength, or shear strength, referring to the magnitude of a particular stress necessary to cause deformation (**Figure 3.30**). Before an earthquake, rocks undergo stress, followed by strain (deformation). Rupture of the rocks can produce an earthquake. Explaining this phenomenon further is beyond the scope of our discussion here, but you will encounter it if you take structural geology or a course in earthquake geology.

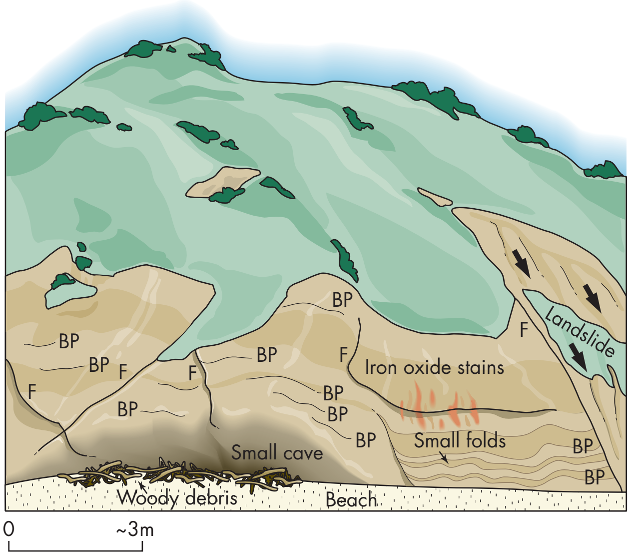
3.9 Rock Structures

There are many types of rock structures. Common structures include fractures, folds, and unconformities. We will discuss each in turn.

Fractures

Two common types of rock fracture are *joints*, along which no displacement occurs, and *faults*, along which displacement has occurred (see Chapter 6). Several rock fractures, in this case joints, are shown in **Figure 3.31**. A fault that displaces rock on Santa Cruz Island in Southern

(a)



(b)

FIGURE 3.31 Fractures and folds (a) Light brown shale along a southern California beach. (b) Drawing showing several properties of the rock: fractures (F), folds, iron oxide stains, bedding planes (BP), and small landslide. *(Edward A. Keller)*

California is shown in **Figure 3.32**. Fractures in rocks, which vary from small hairline breaks to large fault zones up to a kilometer or so wide and hundreds of kilometers long, have environmental significance because:

- They are conduits for fluids, most often water, possibly including pollutants.
- They are zones of weakness in rocks. Fractures generally lower the strength of a rock and, thus, its suitability as a foundation for everything from buildings to bridges, dams, and runways for aircraft.
- Once a fracture has developed, it is subject to weathering, which widens it and may produce unstable clay minerals that may easily wash out or facilitate landslides. When large displacements of 1 m (3.3 ft) or so occur on fractures, large earthquakes are produced (see Chapter 6).

Folds

When rocks are shortened by lateral compression, a series of folds may develop. As a demonstration, push horizontally on a tablecloth and observe the series of arch-shaped convex folds, called *anticlines*, and bowl-shaped concave folds, called *synclines*, that form. These folds are shown on **Figure 3.33a** and will be discussed in greater detail with earthquakes in Chapter 6. If active folding is presently occurring in an area, a series of linear anticlinal ridges separated by synclinal valleys may be present, as shown in Figure 3.33a. At the surface folds are eroded by running water (geologist say the fold is breached). Differential erosion can produce interesting topographic expression of a fold as shown in Figure 3.33b. A series of folds is a *fold belt*, and the basic structure that produces linear valleys and ridges can remain as part of the landscape for several hundred million years. The long-lasting nature of a fold belt is illustrated by the eroded fold belt that part of the Appalachian Mountains formed in the southeastern United States (Figure 3.33c; also see Chapter 2). The Appalachian Mountains formed when Europe collided with America over 200 million years ago. The harder rocks formed linear ridges, and the softer rocks formed the linear valleys of the Appalachian landscape we observe today. These linear ridges and valleys played an important part in our Civil War; armies might have been only a ridge apart without necessarily knowing each other's position.

Unconformities

An *unconformity* is a significant break or gap in the geologic record. It is a time when erosion rather than deposition occurred. Unconformities are important in understanding the geologic history of a

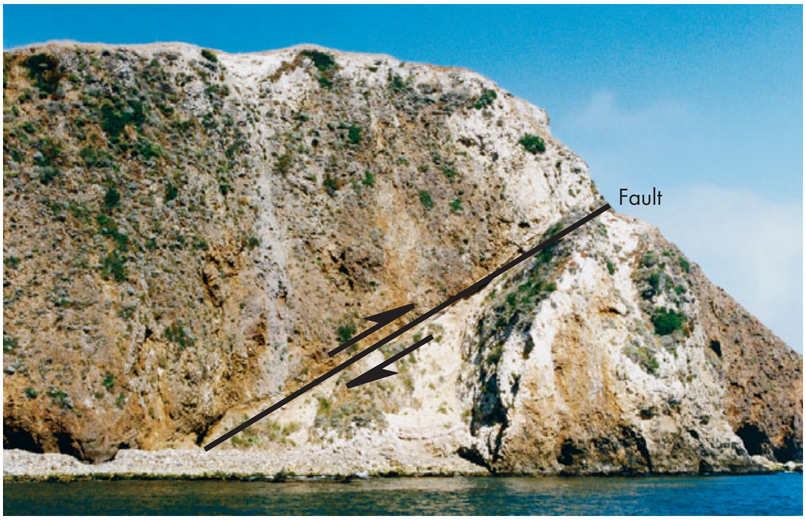
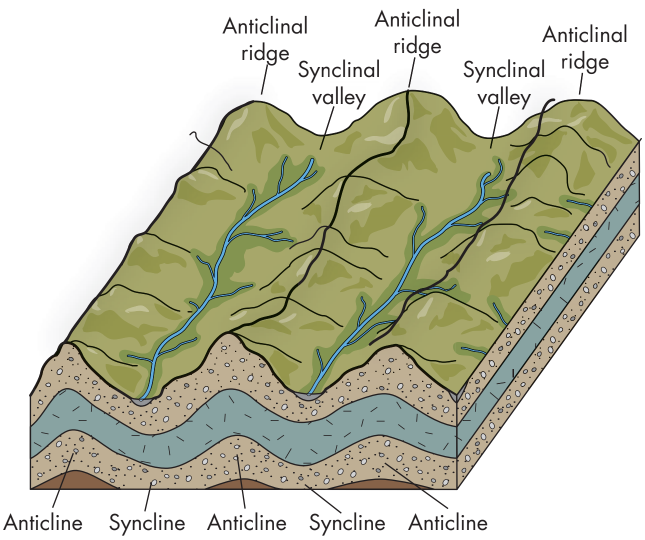
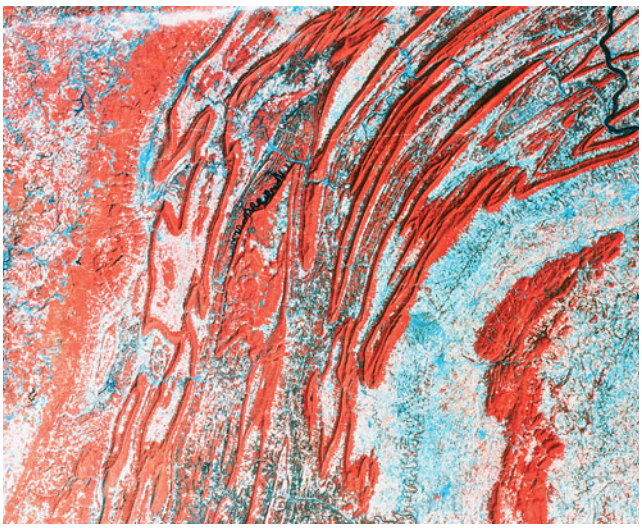


FIGURE 3.32 Fault outcrop (natural exposure) Fault on the eastern coast of Santa Cruz Island, California. Arrows show direction of relative displacement. *(Edward A. Keller)*



(a)

(b)



(c)

FIGURE 3.33 Anticlines and synclines (a) Block diagram of anticlines and synclines. (b) In areas with surface expression of active (present) folding, anticlines often form elongated hills and anticlinal ridges such as Sheep Mountain anticline, Wyoming. *(Michael Collier)* (c) High-altitude image of the fold belt of the Ridge and Valley Province of the Appalachian Mountains of the eastern United States. *(Earth Satellite Corporation/Science Photo Library/Photo Researchers, Inc.)*

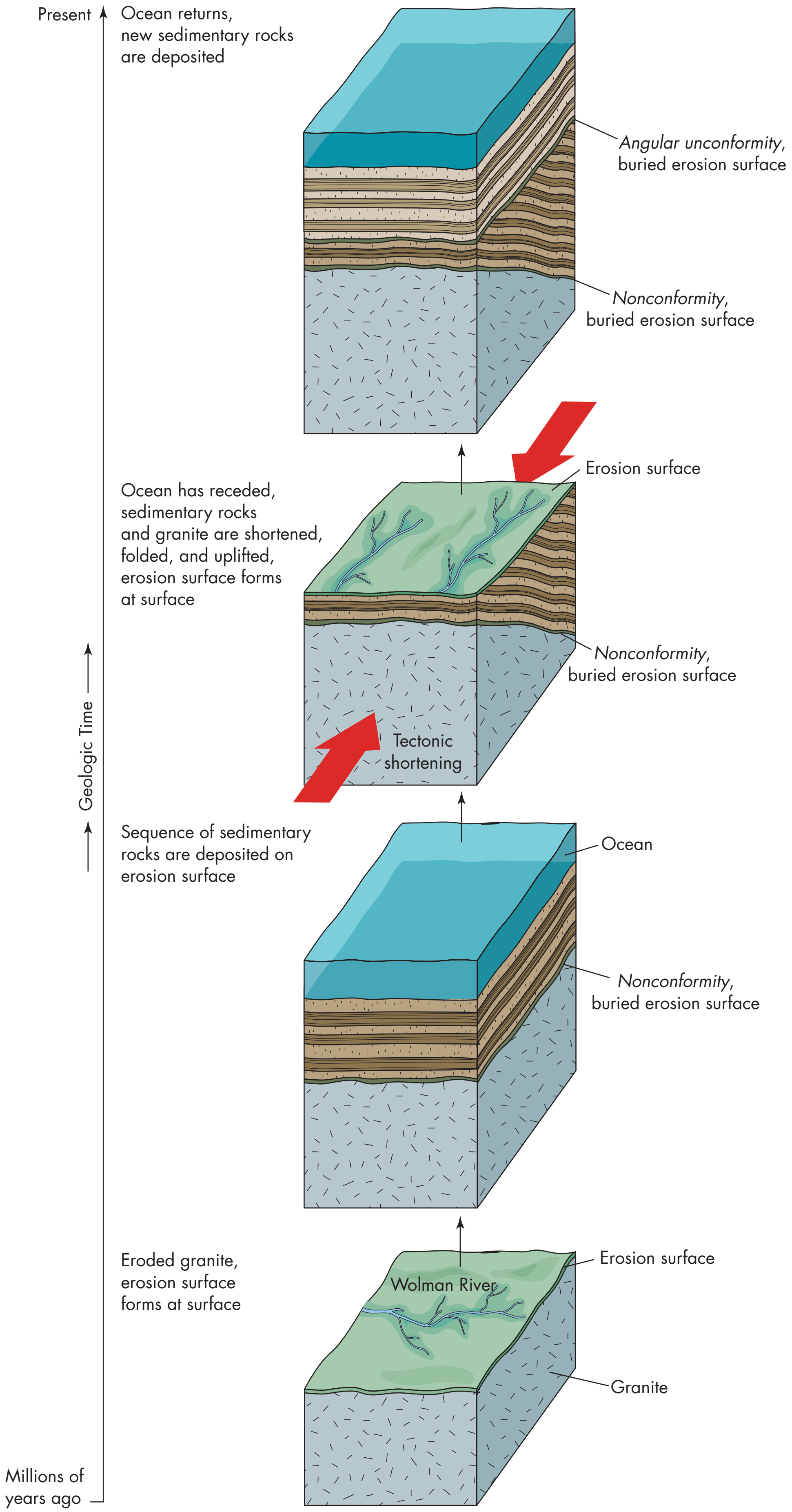


FIGURE 3.34 How unconformities may form Block diagrams showing how a nonconformity and angular unconformity may form.

FIGURE 3.35 Angular unconformity Angular unconformity between older, more tilted sedimentary layers and younger sedimentary layers. *(Edward A. Keller)*

region; they are also important because they are often a natural boundary between two rock types with different characteristics. Springs and oil deposits are sometimes associated with unconformities where downward-migrating water or upward-migrating oil is pushed to the surface.

Unconformities represent a time period when erosion was occurring, and an *erosion surface* may have developed if the land was above sea level. Today, all land on Earth that is above sea level is part of an erosion surface. For example, the Piedmont province in the southeastern United States is a developing erosion surface. If sea level were to rise and cover the land near Charlotte, North Carolina, the igneous and metamorphic rocks that are millions of years old would be buried by young marine sediments. The then-buried erosion surface would be recognized as an unconformity in the rock record. There are three types of unconformity:

- *Nonconformity:* A nonconformity forms between older igneous or metamorphic rocks and younger sedimentary rocks (**Figure 3.34**).
- *Angular unconformity:* Younger sedimentary rocks are located upon an erosion surface, below which older sedimentary rocks are tilted or folded (Figures 3.34 and **3.35**).
- *Disconformity:* A disconformity is formed as an erosion surface between parallel layers of sedimentary rock. They may be difficult to recognize as there may be little visible discontinuity compared with nonconformity and angular unconformity.

Making The Connection

Linking the Opening Case History About Asbestos to the Fundamental Concepts

Consider and discuss the following questions:

1. How does population growth link with the asbestos controversy?
2. What are the implications of science and values to the asbestos controversy?

Summary

Minerals and rocks are the basic building blocks of the solid Earth and form some of our most basic resources on which we rely heavily for our modern civilization. Minerals and rocks also play an important role in many Earth surface processes, such as landslides, earthquakes, and volcanic activity. Finally, the study of minerals and rocks provides important information concerning the history of Earth.

A mineral is a naturally occurring, normally crystalline element or compound formed by geologic processes. Although there are more than 4,000 minerals, we need to know only a few of them to identify most rocks and help evaluate environmental problems. The major groups of minerals of interest to environmental geology are silicates, oxides, carbonates, sulfides, and native elements.

Rocks are aggregates of one or more minerals that are classified into three general types or families, according to how they were formed in the rock cycle. These are igneous, sedimentary, and metamorphic. These three rock types are constantly being created and destroyed as part of the rock cycle. The rock cycle is intimately related to plate tectonics.

Three important rock laws fundamental to understanding Earth history are (1) the law of crosscutting relationships, (2) the law of original horizontality, and (3) the law of superposition.

Igneous rocks are rocks that crystallized from magma. They can be either extrusive, meaning that they cooled at the surface of Earth, or intrusive, meaning that they cooled beneath Earth's surface.

Sedimentary rocks form from parts of other rocks or by chemical processes. They can be either detrital, formed from the lithification of rock fragments, or chemical, produced when chemical or biochemical processes cause solid materials to form from substances dissolved in water.

Metamorphic rocks are rocks changed by heat, pressure, chemically active fluids, or some combination of those factors. They can be foliated, having layered or banded alignment of mineral grains, or nonfoliated, with mineral grains lacking layering or banding.

Minerals and rocks have physical and chemical properties that may have environmental importance. Examples include the relationship between pyrite and acid mine drainage, calcite/limestone and cavern formation, basalt and lava tubes, and schist/foliation and landslides.

The strength of a rock depends upon several factors, including composition, texture, structure, and where it is in or on Earth.

Common rock structures include fractures, faults, folds, and unconformities. These structures may have important environmental consequences.

Weathering is the physical breaking apart or chemical decomposition of minerals and rocks at or near the surface of Earth by physical, biological, and chemical processes. Weathering is most important in the formation of soils, preparation of Earth materials for transport by surficial processes, and transformation of feldspar minerals to clay minerals.

Key Terms

igneous rock (p. 86)
law of crosscutting relationships (p. 86)
law of original horizontality (p. 86)
law of superposition (p. 86)
metamorphic rock (p. 94)
mineral (p. 76)
rock (p. 84)
rock cycle (p. 84)
sedimentary rock (p. 90)
weathering (p. 77)

Review Questions

1. What is a mineral?
2. Define *weathering*.
3. Define *clay*.
4. Define *rock*.
5. Differentiate between igneous, sedimentary, and metamorphic rocks.
6. What are the major components of the rock cycle?
7. What is the law of crosscutting relationships?
8. State the laws of original horizontality and superposition.
9. Define *batholith* and *pluton*.
10. How might a porphyritic texture be produced?
11. What is the difference between a detrital and a chemical sedimentary rock?
12. What factors determine the strength of a rock?
13. What factors contributed to the failure of the St. Francis Dam?
14. What are the main rock structures?
15. How might an angular unconformity be produced?

Critical Thinking Question

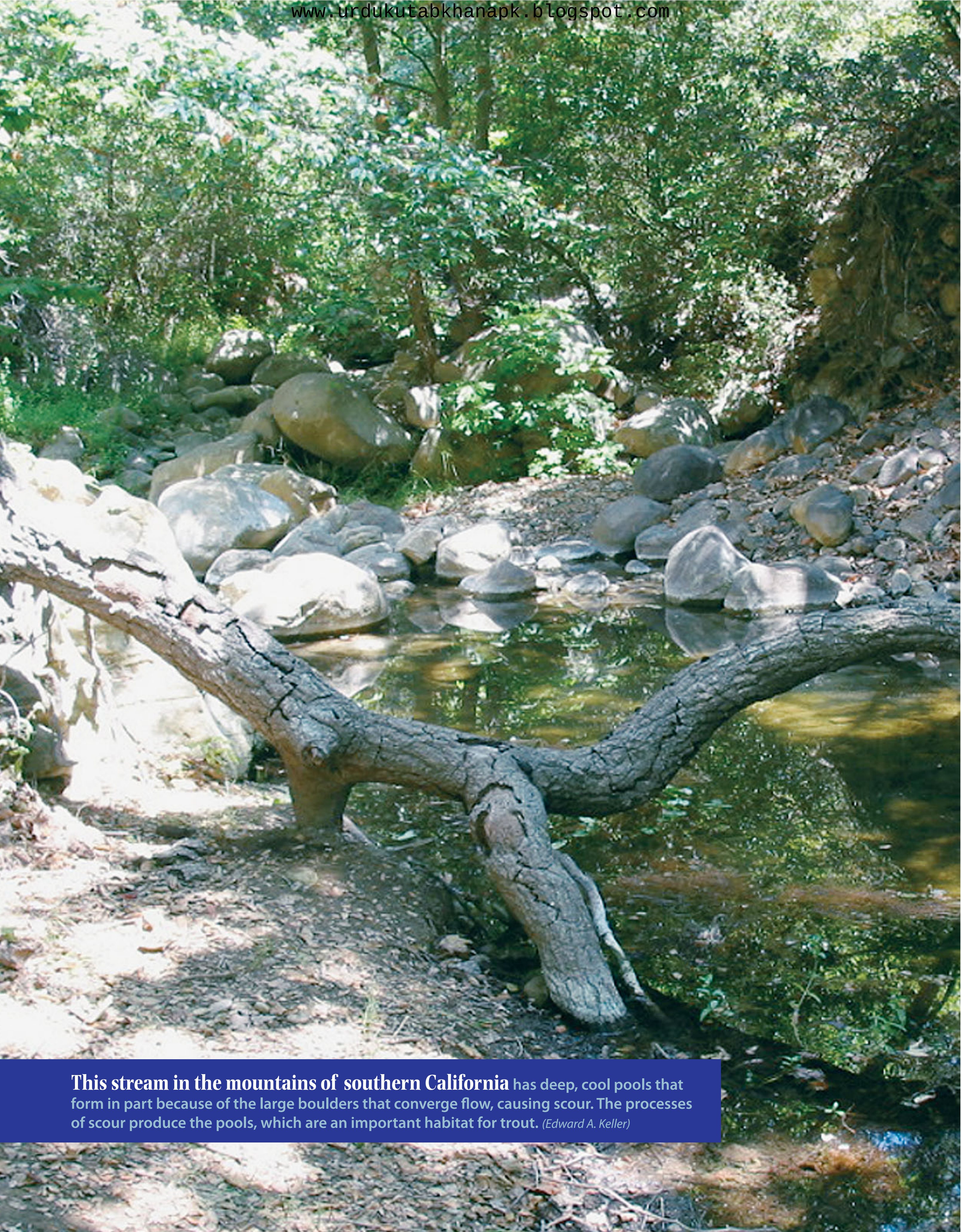
1. Consider the case history concerning the use of asbestos and the need to remove white asbestos, which is not thought to cause environmental health problems. Suppose you are the superintendent of schools in a school system with many old buildings that contain asbestos: pipes wrapped in asbestos, asbestos ceiling and floor tiles, and fire-retardant asbestos used in the auditorium. What steps would you take to determine whether there is a hazard, and how would you communicate with parents who are worried that their children are being exposed to harmful materials? Outline a plan of action.
2. A town is located in the foothills of a mountain range. The rock types in the city limits and just beyond include basalt, shale, and limestone. As the town grows and expands, what advice could you give planners as to potential geologic problems related to the rocks to be aware of as new buildings and roads are sited? What additional geologic information would be necessary?

Companion Website

www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.



This stream in the mountains of southern California has deep, cool pools that form in part because of the large boulders that converge flow, causing scour. The processes of scour produce the pools, which are an important habitat for trout. *(Edward A. Keller)*

4

Ecology and Geology

Learning Objectives

Ecology and geology are linked in many fascinating and important ways. These linkages and their utility in restoring environments, such as rivers, wetlands, or beaches, are emphasized in this chapter. Important learning objectives are:

- **Know some of the basic concepts of ecology and linkages to geology**
- **Understand the importance of relationships between geology and biodiversity**
- **Know what factors increase and decrease biodiversity**
- **Know what human domination of ecosystems is and how we can reduce the human footprint on the environment**
- **Know why we need an appropriate environmental ethic on a time scale relevant to people today**
- **Know what ecological restoration and the processes of restoration are**

Case History

Endangered Steelhead Trout in Southern California: It's All About Geology

Coastal streams that emerge from southern California mountains and flow into the ocean are not commonly thought of as trout habitat. Steelhead trout are born in mountain streams and travel to the ocean, where they remain for several years before returning to spawn. These fish are more commonly associated with streams of the Pacific Northwest. Nevertheless, populations of steelhead trout exist from San Diego in furthermost southern California north to south of San Francisco, where they merge with their more northern relatives.

Southern California has a semiarid climate, and stream flow is extremely variable. Lower parts of streams often dry up in the summer, and much of an entire stream may dry up during drought years that occur periodically. In wet years, especially following wildfires, floods with large amounts of sediment are common. Headwater streams, following wildfire or landslides, may become choked with gravel that in subsequent years spreads through the system, providing important habitat for fish and other aquatic species.

Summer low flow is particularly important to southern steelhead, which are an endangered species. Adults enter the streams from the ocean during winter months to spawn and may return to the ocean to spawn again in future years. The eggs hatch in the gravel of the stream, and young fish reside in the stream for a period of months to a year or so before the urge to go to the ocean moves them to migrate. As part of a study to evaluate the steelhead habitat in the Santa Monica Mountains near Los Angeles, several stream systems were observed during the summer low-flow months. One of the goals as part of a plan to recover endangered southern steelhead was to identify which streams in the Santa Monica Mountains were most capable of supporting steelhead trout. Several of them, including Malibu Creek and Topanga Creek, were known to have steelhead. The geology of the Santa Monica Mountains was found to be an important factor in enhancing the summer low flow that is the major limiting factor for steelhead survival in southern California. Where aquifers are present and groundwater is forced to the surface due to rock fractures or faults, seeps and springs are more common. It was found that on the scale of the Santa Monica Mountains, the eastern portion of the range offers higher potential for summer low flow due to favorable geology. As a series of offshore faults come on land and cross the streams, more abundant summer low flow occurs. The faults form a barrier to groundwater, forcing the water toward the surface, where it emerges as seeps and springs. During the late fall of 2005, a number of pools were observed in Topanga Canyon (**Figure 4.1**), and no fish were observed in most of the pools. In two or three pools where fish were

4.1 Ecology for Geologists: Basic Terms

Ecology is the study of controls over the distribution and abundance of living things. More generally, ecology is the study of living things (i.e., organisms) and their interactions and linkages to each other and to the nonliving environment. The nonliving environment is largely controlled by physical and chemical processes related to the geologic cycle (see Figure 3.13). The complex interactions between life and the broader environment are responsible for the creation and maintenance of our living world. Geologic processes from the global to the regional down to the smallest scales, such as a rock under which a lizard lives, greatly affect life processes.

Discussion of relationships between ecology and geology starts by defining a few terms and principles—including *species*, *population*, *ecological community*, *habitat*, and *niche*. Following these definitions, we will turn our discussion to ecosystems where geology plays a full role in partnership with life. A *species* is a group of individuals capable of interbreeding. *Population* may be defined as a group of individuals of the same species living in the same area. The *ecological community* is a group of populations of different species living in the same area with varying degrees of interaction with each other. We use the

observed, seeps and springs from fractures and faults in the sedimentary rocks were clearly providing a source of cold water. The pools occurred at places where rock banks and large boulders were in the channel. The rocks and boulders constrict the channel, producing a zone of fast water at high flow that scours a pool, providing a low-flow habitat for fish.

The study of the Santa Monica Mountains suggests that it is important to consider geologic factors in streams when assessing fish habitat. In southern California, it is clear that the geology and groundwater are important in understanding fish habitat.

FIGURE 4.1 Fish habitat: It is about geology This pool in Topanga Canyon is at a site where fractures and faults cause springs that introduce cold water into the stream system. Without this cold water, there would be much less habitat for the endangered southern steelhead. *(Edward A. Keller)*

term *habitat* to denote where a particular species lives; how it makes a living is known as its *niche*. For example, think about a mountain lion in the mountains of Montana. We say the habitat is the mountains, and the niche of the mountain lion is eating deer and other large mammals.[1]

Before leaving our discussion of some of the basic terms of ecology, we will briefly consider types of species. Some species are considered to be indigenous, in that they are found in the area where they evolved. Others are exotic species brought into an area or a region by humans for a variety of purposes or as accidentals. For example, acacia trees were brought to the United States and planted as wind breaks in arid regions. Two varieties of eucalyptus trees from Australia have been imported and widely planted, as have been numerous other plants and animals from around the Earth. Most exotic species when introduced do not cause problems, but some do. Sometimes, we refer to problem exotic species as invasive species. These species will compete with indigenous species and may displace them. Some invasive species are brought in accidentally due to transporting material around the world, whereas others are brought in intentionally. In either case, negative aspects of invasive species are often not anticipated. Introduction of invasive species is one of the major reasons for the extinction of plants and animals around the globe.

Two other terms that are useful are biosphere and biota. The *biosphere* is the part of Earth where life exists, and *biota* refers to all organisms living in an area or region up to and including the entire Earth. With these basic definitions behind us, we will consider what an ecosystem is, types of ecosystems, relationships between geology and biodiversity, and human domination of ecosystems.

What Is an Ecosystem, and How Does It Work?

An **ecosystem** is an ecological community and its nonliving environment in which energy flows and chemicals (e.g., nutrients, water) cycle. Thus, an ecosystem involves geology, chemistry, and hydrology, and its functional linkages with life are many and complex. The basics of this are shown in Figure 4.2. It is important to remember that energy flows through ecosystems where chemicals are recycled and used numerous times. Sometimes we refer to "ecosystem function," which is rates of flow of energy and cycling of nutrients or other chemicals through an ecosystem. In addition to ecosystem function, other characteristics are structure, process, and change. Ecosystem structure includes two parts: the community of organisms and the nonliving (geologic) environment. The two main processes of ecosystems are energy flow and chemical cycling. Finally, succession is an orderly and sometimes not-so-orderly change of species as an ecosystem evolves, following a disturbance such as volcanic eruption, flood, or wildfire. If the disturbance results in a new land surface, such as new land added to an island by volcanic eruption, the succession is called *primary*. More commonly, disturbance involves reestablishment of existing ecosystems following disturbance and is called *secondary* succession. Secondary succession often involves plants that are called *pioneers* because they can do well with a lot of light and grow quickly. With time, as more nutrients are cycled and the system develops, the middle stage of succession occurs; this is characterized by the greatest number of species and their ability to use energy

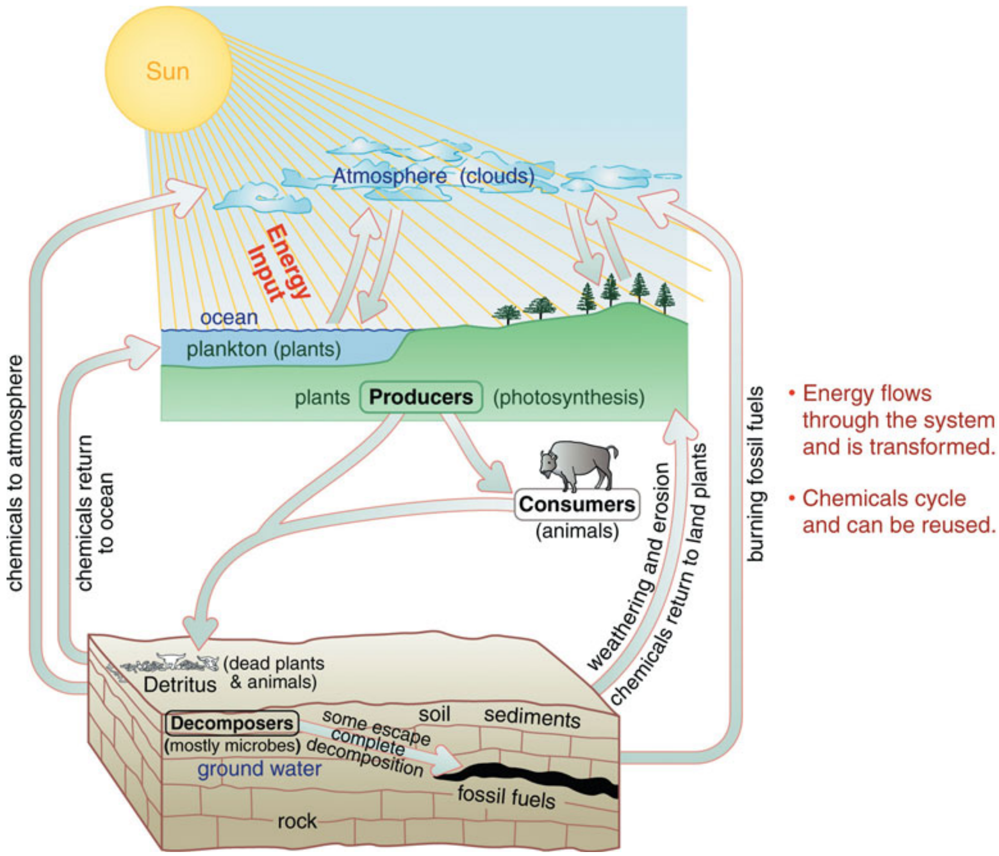


FIGURE 4.2 Ecosystem basics Idealized diagram showing the basics of an ecosystem in terms of energy flowing and chemicals cycling. *(Edward A. Keller)*

and cycle material. The later stages of succession are dominated by fewer species, and in a forest we say these are the *old growth*. The popular idea of a "balance of nature" with orderly succession to a climax condition where little changes and the system is in equilibrium is an imaginary condition and a concept largely rejected by ecologists. Disturbance and change on a variety of scales of time and space are the norm.[1]

There are several types of ecosystems, including indigenous, natural, human modified, and human made or constructed. Completely natural indigenous ecosystems on land are hard to find because human activity has been so pervasive or invasive that almost all ecosystems have been modified by human use and interest. For example, some of the waste of our society, such as lead that is emitted into the atmosphere, is transported around the planet, affecting all ecosystems it comes into contact with, often far from human populations.

Some ecosystems, over a wide range of sites and purposes, are constructed by humans. For example, we may construct shallow ponds or a series of canals known as bioswales that collect runoff of surface water. Marsh plants, such as cattails, when planted in ponds or canals, use and remove nutrients in water that's delivered to them as a waste or pollutant, helping clean the water. Specially designed wetland ecosystems have been constructed where bacteria and plants process mine wastewater and help remove toxins from water. Other large-scale ecosystems are constructed to partially treat urban wastewater. Human-constructed ecosystems are part of what is known as *biological engineering*.

Natural Service Functions of Ecosystems

Earth is a suitable place to live because the environment produces the necessary resources that living things need to survive. As one of the many species on Earth, we extract resources and receive the benefits of natural service functions from ecosystems (also called ecosystem services). By *natural service functions*, we mean those processes of ecosystems that are responsible for producing clean water and air, as well as the mixtures of plants and animals that are necessary for our survival. For example, ecosystem services help cycle elements through the environment, provide nutrients to plants, remove pollutants from water, and, through soil fertility, allow for increased crop production.

Natural service functions may include buffering functions, such as protection from natural hazards such as landsliding and flooding. For example, plants on steep slopes contribute to soil stability through the interaction of growing roots in the soil that increases the strength of slope materials and provides protection from failure by landslide. The roots, especially those with a diameter about the size of a pencil's, bind the soil together much like steel bars in concrete. Similarly, plants on the banks of a stream provide a root mass that stabilizes the soil and helps retard stream-bank erosion. Freshwater or saltwater marshes provide a buffer that absorbs wave energy and energy from winds. Coastal marshes protect against coastal flooding and also help reduce coastal erosion.

We have grown accustomed to the natural service functions that the ecosystems of Earth provide. On the other hand, we sometimes change the land and reduce or eliminate these service functions. For example, when we remove coastal marshes, we are more vulnerable to coastal erosion and flooding from storms, such as hurricanes, that occasionally strike the coastline. When we drain marshes and wetlands along rivers, we reduce their ability to store water and, as a result, increase the flood hazard.

4.2 Geology and Biodiversity

Biodiversity is an important concept in environmental science. Most commonly, when we think about biodiversity, we are discussing the number or abundance of species in an ecosystem or ecological community. The number of species is often referred to as *species richness*, whereas the relative proportion of species in an ecosystem is referred to as its *species evenness*. Another term sometimes encountered is *dominant species*, which is the species or multiple species that would be most commonly observed in an ecosystem. Plant ecologists use the concept of importance value of a species or multiple species to an ecosystem. The important principle with respect to biodiversity is that geology influences biodiversity from the smallest scale on a hill slope to continental-scale features, such as a mountain range.

Biodiversity of Trees in North America and Europe

A fascinating and interesting relationship between geology and biodiversity at the continental scale is the distribution and number of native tree species in North America versus Europe. North America has many more native species of trees than are found in Europe, and the hypothesized reason is related to linkages between the ice ages, glaciers, and plate tectonics that determine the orientation of mountain ranges. In North America, the major young mountain ranges run generally north–south and include the Rocky Mountains and the mountains of the West Coast. In Europe, the dominant young mountain ranges resulted from the collision between the African and European plates that produced the Alpine range in Spain east through the Himalayas (**Figure 4.3**). So how might this be related to the number of species of trees in North America and Europe?

The Last Glacial Maxima about 20,000 years ago, when glacial ice covered about 30 percent of the continental area, was a harsh environment for trees. As the continental glaciers grew in North America and Europe, the trees had to migrate in front of the advancing ice. In North America, they found corridors to migrate to the south, but in Europe they were blocked by the east–west Alps that were glaciated. In Europe, the trees became trapped between the glaciers, and many more species became extinct than in North America. Thus, we see that the biodiversity of native trees in North America and Europe was significantly affected by continental-scale mountain building related to plate tectonics.[2]

Community Effects and Keystone Species: How Are These Concepts Related to Geology?

Two or more organisms may interact in complex ways to affect other organisms in an ecosystem. These organisms are further linked to the nonliving environment and combined ecosystem functions (e.g., rates of flow of energy, cycling of nutrients) in ways that help maintain the system. Some individual species have a strong community effect with an influence disproportionate to their abundance. We call these species *keystone species*, and there are many examples of relationships between geology

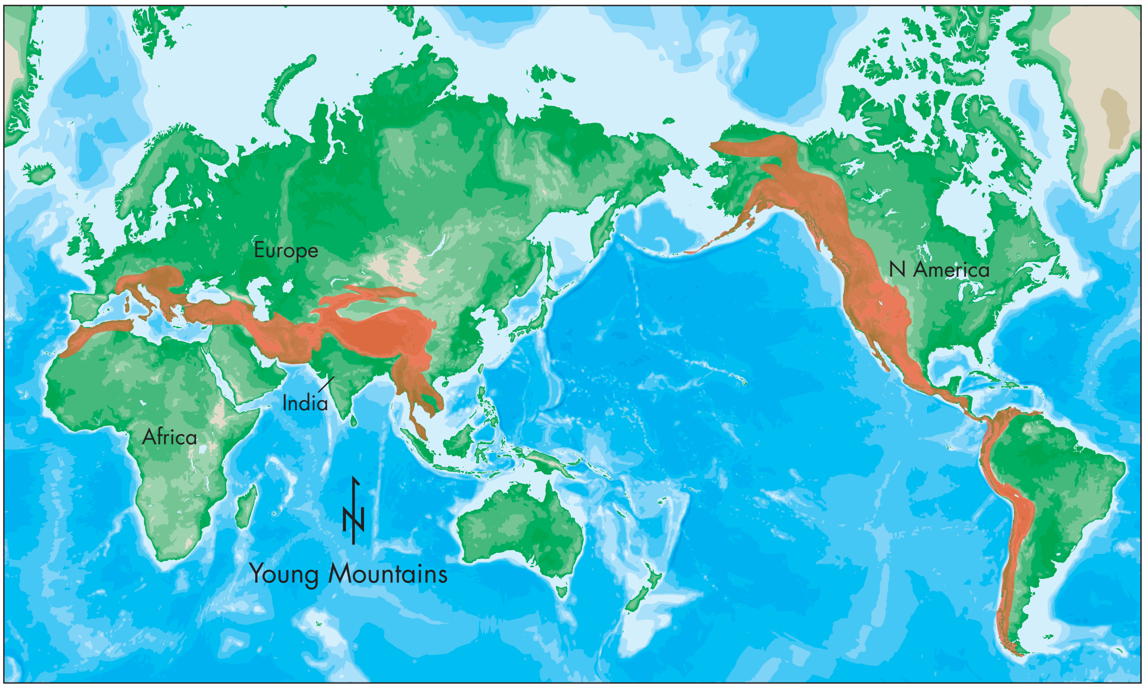


FIGURE 4.3 Major young mountains on Earth A map showing the major young mountain ranges. Notice that mountain ranges in North America are roughly north–south, and the major mountain ranges in Europe, the Alps and Himalayas, are much more east–west. *(Edward A. Keller)*

and keystone species that help maintain ecosystems and biodiversity. We will discuss two of them: stream processes in Yellowstone National Park and the kelp forest of southern California.

Stream Processes and Ecology: Story of Mountain Streams, Elk, and Wolves in Yellowstone National Park

A mountain stream is a robust system consisting of the stream channel, bed, and banks composed of silt, sand, gravel, and bedrock. Cool, clean water is supplied by the geologic environment through snowmelt and rain that infiltrate the rocks and soil to emerge in the stream as a series of seeps or springs. This water provides the summer low flow. The water itself supports life in the stream, including fish and other organisms, as well as streamside vegetation in the riparian environment, which refers to the environment adjacent to stream channels that is different from the adjacent uplands. Stream bank vegetation also helps retard erosion of the banks and the introduction of an adverse amount of sediment into the stream system. Some of the riparian vegetation, such as cottonwood and willow trees, is prime food for animals, such as deer and elk, that browse on the plants. If there is too much browsing, the abundance of trees will be dramatically reduced; this damages the stream environment by reducing the shade to the stream and also increases bank erosion and introduces harmful fine sediment into the water. Fine sediment (e.g., silt) is a type of water pollution because it reduces soil resources (i.e., it is a product of soil erosion), degrades water quality, and can directly clog gills of aquatic animals. In the stream bed, fine sediment may fill the spaces between gravel particles or seal the bed with mud, damaging fish and aquatic insect habitat.

The above scenario was played out in Yellowstone National Park between the 1960s and 1990s, during a period when wolves were not present and elk were not culled. The willows and other streamside vegetation were greatly denuded by browsing elk. Then, in the mid-1990s, wolves were reintroduced to the Yellowstone National Park ecosystem. Observations by wildlife scientists reported that wolves were more successful in hunting elk in areas where the elk had to negotiate more complex, changing topography, common along the streams where the elk were feeding. The elk soon responded and avoided the stream environments except when absolutely necessary. Over a 4-year period, from 1998 to 2002, the percentage of willows eaten by elk dropped from about 90 percent to nearly zero. It is expected that, as the streamside vegetation contributes to recovery, the stream channel and banks will also recover to become more as they were prior to the 1920s, when the last wolves in Yellowstone were killed (**Figure 4.4**). Although the reintroduction of large predators, such as wolves, is controversial, the wolves play a role in the ecosystems in which they are present. Wolves, by hunting elk and scaring them away from the streams, exert a positive force that improves the stream banks and water quality (**Figure 4.5**). Thus, wolves are a keystone species and affect the broader community of organisms. Wolves are not interested in protecting the streamside environment, but through hunting elk

FIGURE 4.4 Wolves and streams (a) Willows along Blacktale Creek in the spring of 1996 are nearly absent because of heavy browsing by elk. *(William J. Ripple)* (b) Following reintroduction of wolves only 6 years earlier, thicker stands of willows are clearly evident. *(William J. Ripple)*

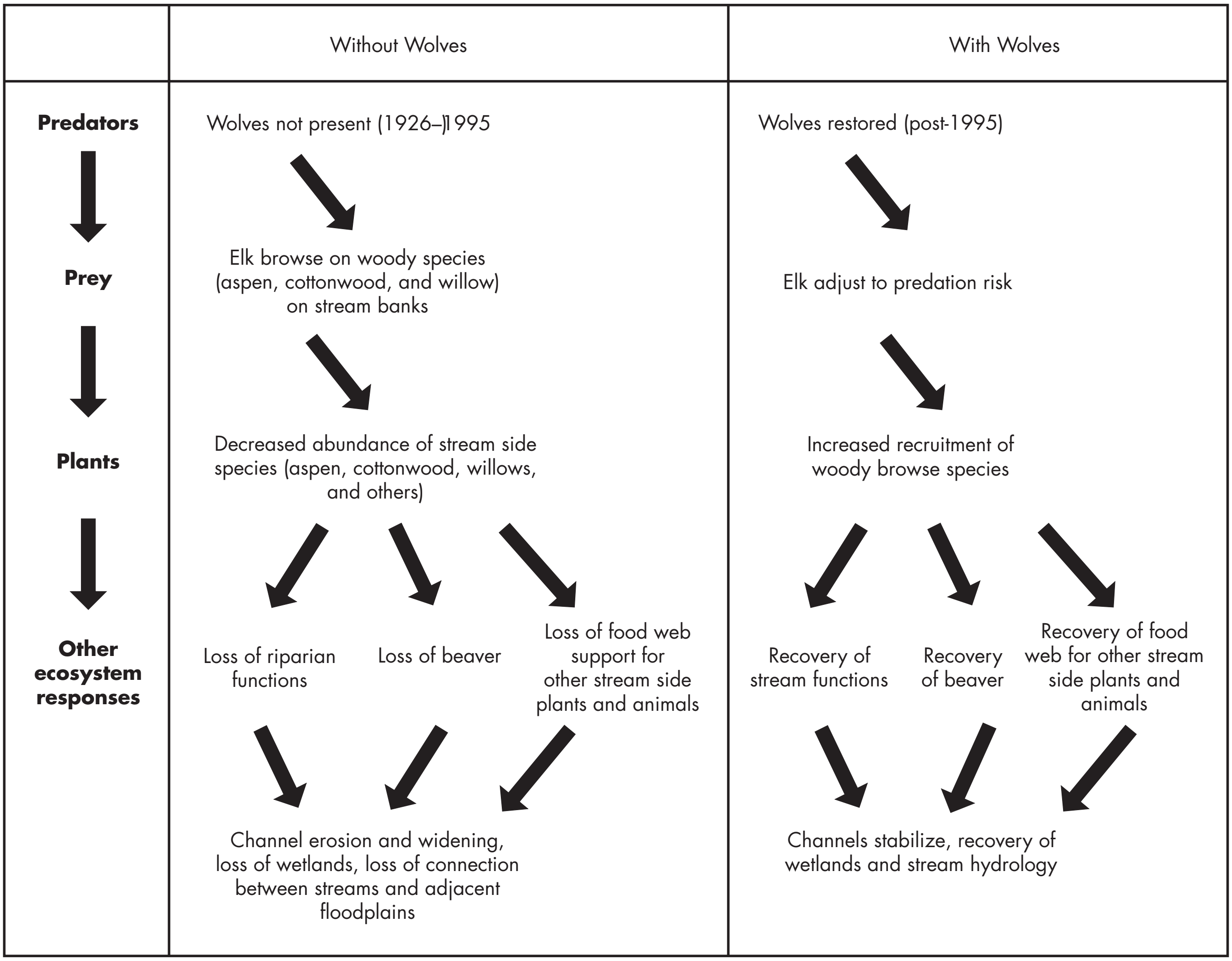


FIGURE 4.5 Ecosystem processes with and without wolves Diagram showing processes that occur with and without wolves for streams in Yellowstone National Park. Without wolves, extensive browsing by elk degraded this stream environment, which has recovered since wolves have been reintroduced. *(Modified after Ripple, J. W., and Beschta, R. L. 2004. Wolves and the ecology of fear; can predation risk structure ecosystems?* BioScience *54(8):755–766)*

(Figure 4.6), they help maintain a higher-quality stream environment.[3]

Coastal Geology, Kelp, Urchins, and Sea Otters

The kelp forests in southern California (Figure 4.7) are a remarkable ecosystem based in part on the local geology. Kelp are a type of large marine alga that grows incredibly fast. The giant kelp of southern California can grow up to more than 25 cm per day, reaching a height of over 10 m above the seafloor. The three parts of the kelp plant include the root-like holdfast, stem (i.e., stipe), and system of blades (i.e., leaves). Kelp also have a number of flotation devices near the blades so they will remain in an upright position in the water column. At the surface, particularly at low tide, the sea surface looks like a nearly solid mat of kelp. Below the surface, the forest consists of stipes, which are attached to the bottom by the holdfasts. Holdfasts attach to boulders or the rocky bottom. Some of the rocky environments to which they may become attached are wave-cut platforms found offshore in fairly shallow water and rock reefs, which may have water depths of up to several tens of meters. The wave-cut platform

FIGURE 4.6 Natural predators Wolves are natural predators of elk in Yellowstone National Park, and their reintroduction has benefited stream ecosystems in unexpected ways. *(Tom McHugh/Photo Researchers, Inc.)*

has variable relief depending upon the local resistance of the particular rock shelf. Rock reefs often result from geologic uplift from faulting or the presence of more resistant (hard) rock. From Santa Barbara south to Los Angeles, these structures are parallel to shore and roughly east–west. Nearly all the offshore reefs that support kelp forests owe their existence to an active geologic environment.

Holdfasts are attached to the rocks with what looks like a root system, but they do not take up nutrients. Rather, the function of holdfasts is to hold the plant in place. If the holdfasts break loose or are destroyed by some process, the kelp will float free and drift to the shore. During storms, the kelp moving near the surface will apply stress to the lower plant, causing the holdfast to come loose. The holdfast, with bits of rock, may be transported to the beach to become part of the sediment carried in the near-shore environment. This process can move rock particles from offshore to the beach, while distributing organic material from offshore to the beach.

The kelp forest flourishes in areas of upwelling nutrients and relatively cold water. Growth rates are greatly reduced in years when the marine water warms up, such as during El Niño years, when warmer water is present. A variety of organisms live near the bottom of the kelp forest, including urchins, which are spiny animals that feed on the holdfasts of kelp. When urchins feed and break the holdfasts, the

FIGURE 4.7 Kelp forest The kelp forest of southern California is a remarkably diverse ecosystem. Geology plays an important role in the development of the kelp forest, in which the plants are attached to the ocean bottom in relatively shallow water of wave-cut platforms or uplifted rock reefs. *(Mark Conlin VWPics/SuperStock)*

FIGURE 4.8 Sea otters and the kelp forest Sea otters are a keystone species of the kelp forest. They feed on urchins and other shellfish. *(Bill Curtsinger/National Geographic Images/Getty Images)*

kelp will float free and die. There are several predators of sea urchins, including humans, who collect them for their roe (i.e., eggs), which is valuable, and sea otters, who eat the urchins (**Figure 4.8**).

Studies conducted in Alaska suggest that areas which no longer have many otters are impoverished. In some areas, the sea urchins are so plentiful that kelp scarcely exists. Where sea otters have been restored to their former range after they were nearly exterminated for their valuable fur, the kelp returns and flourishes.[1] Linkages between the geologic environment, kelp forest, urchins, and sea otters are idealized in **Figure 4.9**. Notice that when sea otters are

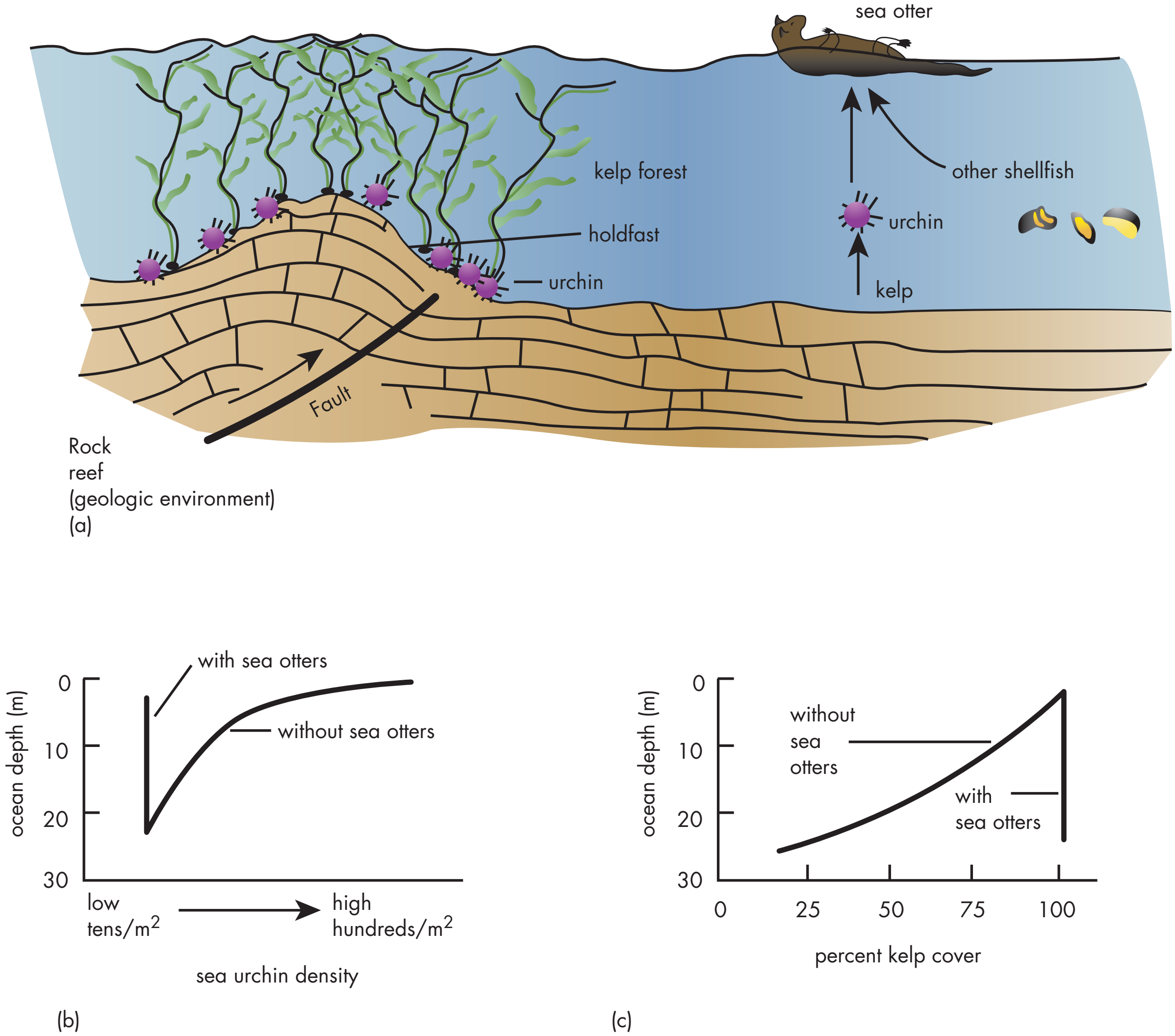


FIGURE 4.9 Sea otters and the kelp forest Idealized diagrams showing the effects of sea otters on the kelp forest and, in particular, the abundance of kelp. (a) The geologic environment with uplifted rock reef, kelp, urchins, and sea otters. (b) Without sea otters, the density of urchins is high. (c) With sea otters, the percentage of kelp cover is high. Notice that when sea otters are absent, there is a large reduction in the kelp.

present, there are fewer urchins and there is more abundant kelp.

Sea otters are a keystone species with a strong community effect because when they eat sea urchins, they make a healthy kelp forest more likely. The kelp forest and exposed rock provides the structure and food resources for other animals, including fish. Sea otters have no interest in protecting kelp, and they don't hang around at the base of the kelp, keeping the urchins off. However, through their feeding on urchins, sea otters help ensure a healthy, productive kelp forest.[1]

There is currently a controversy about whether sea otters should continue to expand into their previous habitat in southern California south of Pont Conception, northwest of Santa Barbara. People harvest urchins, and fishermen are afraid that, if sea otters become abundant, the number of urchins will be reduced to the point that it will not be profitable to harvest them. The sea otters, of course, are unaware of this controversy and are simply moving back into their historic habitat. If the sea otters are allowed to migrate south, their reestablishment will be a slow process and, in fact, may not occur for a variety of reasons. First and foremost, the coastal waters in some areas of southern California are polluted, and pollutants may sicken the sea otters. Also, the climate is changing, and ocean waters are warming, which may make the southern regions of the habitat less viable for kelp forests and the urchins that feed on kelp holdfasts. In addition, sea otters are sensitive to water temperature. They have high fat density that provides good insulation in cold water but can result in overheating in warm water.

Our discussion of wolves in Yellowstone and sea otters in the kelp forest and their relations to the hydrologic and geologic environment is fairly straightforward. There are numerous other examples of how keystone species affect ecosystems. For example, American bison, through their grazing practices, helped maintain biodiversity of the tall grass prairie and the soil where they roamed (**Figure 4.10**).

Some species that are not large individuals or highly visible in their ecosystems have large importance from an ecological perspective. For example, reef-building coral and algae are species that create physical habitat in the coral reef environments of the world. The coral and algae provide the framework upon which other reef life exists (**Figure 4.11**). Due to warming of the oceans, pollution, and overfishing, coral reefs around the globe are in decline in many places. Finally, ancient coral reefs are present as limestone rock that forms the foundation of many areas where people live, including much of Florida and the Great Lakes area.

FIGURE 4.10 American bison American bison greatly influenced the tall grass prairie that they roamed across as they grazed. Their grazing habit helped maintain the biodiversity of the prairie grasses and the entire landscape, including soils and wetlands known as buffalo wallows. *(Jason Langley/Reciprocity Images/iStockphoto)*

FIGURE 4.11 Coral reefs Coral reefs are composed of a number of organisms, including algae and corals, which build up the basic reef structure that greatly affects biodiversity of the marine environment. *(John A. Anderson/iStockphoto)*

Factors That Increase or Decrease Biodiversity

Following our discussion of ecological communities, ecosystems, and keystone species, we can more directly address what sorts of processes are likely to either increase or decrease biodiversity. We are primarily concerned with species richness—that is, the number of species—but biodiversity also relates to genetic diversity, which is the number of genes found in the population that may not always be expressed by the morphology or function of the particular organism.

What Factors Increase Biodiversity?

Biodiversity may be increased by several factors[1], including:

- The presence of diverse habitat with many potential niches. For example, a river with variable depth, turbulence, velocity, and amount of large woody debris (stems and root wads of trees) will support more species.
- Moderate amounts of disturbance—such as wildfires, violent storms, or volcanic activity—that provides new or renewed habitat.
- The presence of harsh environments, such as hot springs or nutrient-poor rocks and soil, may have specialized species that increase diversity at the regional scale.
- Relatively constant environmental factors, such as temperature, precipitation, and elevation. This is one of the reasons there are so many species near the equator. There is a relatively constant supply of energy from the sun near the equator, and conditions such as temperature and humidity are relatively constant, leading to greater diversity of organisms.
- The evolution, or generation of biodiversity, which generally refers to slow changes over geologic time in organisms. However, sometimes evolution can occur rapidly with species.
- An environment that is highly modified by life, such as rich organic soil. At regional scales, more biologically productive areas tend to be more diverse.
- Geology, which affects ecosystem function and process from small- to continental-scale environments. See, for example, the earlier discussion of biodiversity and orientation of mountain ranges.

What Factors Reduce Biological Diversity?

Biological diversity may be reduced[1] by:

- The presence of extreme environments, such as hot springs or tar seeps that locally provide a much more limited set of habitats and niches for life. From above, we see that extreme environments may increase biodiversity at the regional scale. Thus, the effect changes with scale.
- Extreme disturbance or very frequent disturbance, such as regional-scale fires, storms, or volcanic activity, that catastrophically disrupt ecosystems.
- Transformation of the land, which fragments ecosystems. Examples of fragmented ecosystems include; above and below a dam on a river that blocks migration of fish, construction of a large reservoir that leaves a series of small islands isolated from the mainland, and

urbanization of a region that results in few corridors between rural lands for migration of plants and animals.

- The presence of environmental stresses, such as pollution.
- Habitat simplification, such as agriculture that reduces habitat and construction of engineering structures to control flooding or erosion (see A Closer Look: Seawalls and Biodiversity).
- Introduction of intrusive species that compete with indigenous species or cause predation or disease in indigenous species.
- The presence of mountain ranges that block or restrict migration of plants and animals.

Human Domination of Ecosystems

It is apparent that we humans dominate almost all ecosystems on Earth. Study of this domination has led to the general conclusion that the domination has not yet produced a global disaster. However, in some areas, disastrous conditions have occurred. It is apparent that many factors are linked in complex ways to human population increase as well as transformation of the land for human use and global change in climate and the biogeochemical cycles. These processes are resulting in the reduction of biological diversity, including the loss of entire ecosystems and the extinction of many species. We are apparently in a large extinction event that in the past 2,000 years has resulted in a reduction of biodiversity, particularly for birds, mammals, and fish, as well as many insects and other species. The rates of extinction during the past 2 millennia are much larger than would be expected based on geologic background rates.

The most significant factor that has led to human domination of Earth's ecosystems is land transformations. These transformations occur as we develop our agriculture, industry, recreation, and urban centers.

The Golden Rule of the Environment: A Geologic Perspective All About Timing

Stephen Jay Gould, a famous geologist and ecologist, stated that a proper scientific analysis of the environmental crisis facing people today requires the use of an appropriate scale of time and space. Gould argued that there is "Earth time" (deep time), which is basically geologic, and then there is "human time," which is very much shorter and of interest to people on Earth today. He stated that modern human beings are only one of millions of species that have been on Earth and that each species is unique and has its own value. Gould argued that there is an appropriate environmental ethic based upon the issue of the human time scale versus the "majesty but irrelevance" of geologic time.

Gould's basic conclusion is that we need to make a "pact" with Earth (our home) because She holds all the important playing cards and, as such, has a power over us. We are in great need of developing a more compatible relationship with our planet on our time. Earth does not need an agreement with us. Such an agreement would be a gift from Mother Earth to us and is a variation of the *golden rule:* Do unto others as you would have them do unto you. Gould argued that we should cut a deal while Earth is still able to enter into such an agreement on our time scale. He stated, "If we scratch her, she will bleed, kick us out, bandage up, and go about her own business at her own time scale."[5] In other words, if we continue to treat our planet with disrespect, we will eventually degrade the environment for humans and many other living things. As a result, we might become extinct sooner, along with many other species. If we sustain ecosystems and resources, we might avoid extinction a bit longer. From a deep time perspective, over hundreds of millions to billions of years, our species will have little effect on Earth's history. However, on a time scale of interest to us, we would like to hang around as long as possible. We are not talking about saving Earth. Earth will go on at least a few billion more years with or without us! We are talking about sustaining Earth systems that we depend upon for our health and well-being.

What Can We Do to Reduce the Human Footprint on the Environment?

The *human footprint* on the environment is the impact we have on our planet, including its resources and ecosystems. Just recognizing that the human footprint is growing is a step (poor pun) in the right direction. We recognize that our total footprint is

A Closer Look

Seawalls and Biodiversity

A *seawall* is a structure made of concrete, large boulders, or, sometimes, wood constructed parallel to the shore, with the objective of stopping coastal erosion (Figure 4.A). Waves break on the wall (not the exposed beach), reducing coastal erosion. Seawalls cause an initial narrowing of the beach because they physically intrude on the beach. A seawall causes waves and their energy to be reflected. The reflected waves erode sand near the wall, which further narrows the beach. Unless there is a lot of sand available to replace the eroded sand, the beach over a period of years to decades will become narrower and narrower. In some cases, the beach may disappear, except at the lowest tides.

A variety of species use a beach ecosystem. Clams and other shellfish, worms, and sand crabs live below the surface. Animals, including birds and fish, hunt and eat what is in the sand or washed out by wave action. Kelp, driftwood, and other plant debris can be found on the surface, along with sand fleas and insects that feed on the beach debris. When a beach is narrowed by a seawall, all the life is squeezed into a narrower zone. There are fewer animals in the sand and fewer birds to feed and rest on the beach. In addition, the beach has less driftwood and stranded kelp to provide habitat for insects. As a result, biodiversity of the beach decreases.[4] An idealized diagram of the changes is shown in Figure 4.B. The big idea is that, as we reduce habitat of species in an ecosystem, their diversity changes. Some species are reduced in number, and others may disappear. This is especially likely if a beach nearly disappears following construction of a seawall.

FIGURE 4.A Seawall This seawall in southern California is affecting the beach environment by narrowing the sandy beach. *(Edward A. Keller)*

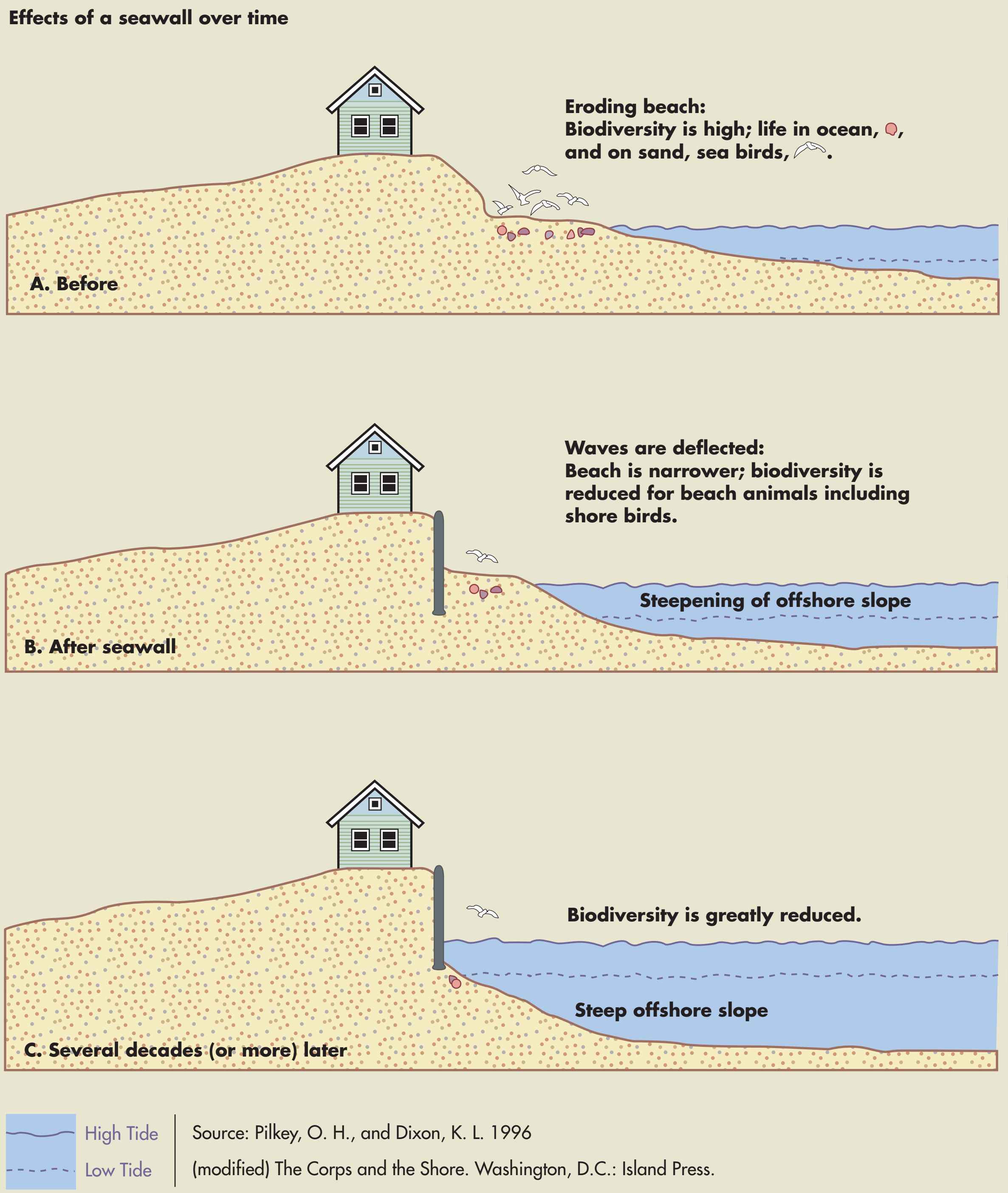


FIGURE 4.B Seawalls and ecology Idealized diagram showing the effect of seawalls on a sandy beach environment over a period of decades. As the beach slowly narrows, the biodiversity is reduced for beach animals, including shore birds. In addition, narrower beaches also have less organic debris, including driftwood, that provides habitat for organisms living on the beach.

the footprint per person multiplied by the total number of persons. In order to reduce this impact, we need to either reduce the number of people or reduce the impact per person. The ways most often mentioned are to reduce human population, use resources more efficiently, and learn to manage our waste better. It is also important to gain a better scientific understanding of ecosystems. We need to know more about how ecosystems are linked to human-induced change and how our sociocultural environment is linked to those changes. When we do this, we recognize the importance of human-dominated ecosystems and their linkages to the broader world. Finally, recognizing that we have a significant footprint, we have a moral responsibility to manage ecosystems better. If we wish to maintain biological diversity of "wild ecosystems" with their "wild species," then we will have to make conscious decisions about how we manage the environment. Particularly important will be more active management because we recognize that the human population increase is unprecedented in Earth's history. Never before has one species so clearly dominated the world. In some cases, changes are increasing and accelerating, and the more we know about these changes, the better prepared we will be for active management of our planet.[6]

4.3 Ecological Restoration

Restoration ecology is the science behind the process of ecological restoration. Our discussion focuses on the application of science (i.e., restoration ecology) to restoration projects. A simple definition of **ecological restoration** is that it is the process of altering a site or an area with the objective of reestablishing indigenous, historical ecosystems. There are many potential restoration projects, including river restoration for fish and other wildlife habitat; dam removal to reunite fragmented river ecosystems (see A Closer Look: Restoration of the Kissimmee River); floodplain restoration to improve ecological function; wetland restoration of freshwater or saltwater marshes for a variety of purposes, from flood control to improving wildlife habitat to providing a buffer to coastal erosion (see A Closer Look: Restoration of the Florida Everglades); beach and coastal sand dune restoration to help manage beach erosion and provide wildlife habitat (see A Closer Look: Coastal Sand Dune Restoration at Pocket Beaches: University of California, Santa Barbara); restoration of habitat for endangered species; reshaping the land, drainage, and vegetation following surface mining; and restoring habitat for native species and wildlife impacted by clear-cut logging or for improved fire management.

A common objective of the restoration process is to change a degraded ecosystem so that it resembles a less human-disturbed ecosystem and contains the structure, function, diversity, and processes of the desired ecosystem. In an attempt to add a human and social component to ecological restoration, it might also be defined as the process of deliberately modifying a site or an area to compensate for environmental degradation caused by humans. The purpose of restoration is to reestablish sustainable ecosystems and develop a new relationship between the natural environment and the human-modified environment.[7,8] When we try to apply these ideas and principles, we come to the realization that many human-altered environments are nothing like natural systems. Furthermore, it is nearly impossible to restore many sites to their initial conditions because they have been irreversibly changed. For example, many coastal wetlands and river wetlands have been drained, filled in, and developed for human use. Returning them to their original condition would be impossible. Therefore, a more practical approach is to attempt to transform the present ecosystems and landscapes into ones that more closely resemble ecosystems less disturbed by human processes. For example, planning to restore a river that flows through a city might include removing nonnative species, replanting native plants, and allowing the river to behave in a more natural state within its floodplain. In doing so, the restoration would produce a greenbelt along a river that is well vegetated and contains portions of ecosystems that were present prior to urbanization. The result would be a compromise between ecological restoration to establish what was there prior to urbanization and the production of a more natural river system that functions more like rivers found in a nonurban environment.[7,8]

It is possible to restore a variety of landscapes, but, regardless of what is being restored, consideration must be given to several major factors that we sometimes call the "Big Three" in restoration: hydrologic process, soils and rocks, and vegetation. Hydrologic process includes the entire hydrologic

A Closer Look

Restoration of the Kissimmee River

Restoration of the Kissimmee River in central and southern Florida is the most ambitious river restoration project in the United States. Prior to channelization, the river was approximately 160 km (100 mi) long, meandering through a floodplain that was several kilometers wide (**Figure 4.C**). The river had an unusual hydrology because it inundated its floodplain for prolonged periods of time. As a result, the floodplain and river supported a biologically diverse ecosystem consisting of wetland plants, wading birds, waterfowl, fish, and other wildlife.

Prior to about 1940, few people lived in the Kissimmee basin, and the land use was primarily farming and cattle ranching. However, rapid development and growth occurred following World War II, and, in 1947, widespread flooding occurred as a hurricane moved through the basin. As a result, the state of Florida requested the federal government to design a flood-control plan for central and southern Florida. The channelization of the Kissimmee River was planned from about 1954 to 1960, and between 1962 and 1971, the river was channelized. Approximately two-thirds of the floodplain was drained, and a canal was excavated, turning the meandering river into a straight canal. As a result of the channelization, ecosystem function was degraded. Wetlands with populations of birds and fish were drastically reduced. Outrage over the loss of the river went on for years before restoration efforts were discussed and planned. The purpose of the restoration is to return a portion of the river to its historic meandering riverbed

FIGURE 4.C Restoration of the Kissimmee River (a) The Kissimmee River in central and southern Florida prior to channelization. *(South Florida Water Management District)* (b) The Kissimmee River following channelization that involved straightening the channel, essentially producing a river as a ditch. *(South Florida Water Management District)*

and wide floodplain. Specific objectives[9] are to:

- Restore historic biological diversity and ecosystem function.
- Re-create the historic pattern of wetland plant communities.
- Reestablish the historic hydrologic conditions with prolonged flooding of the floodplain.
- Re-create the historic river floodplain environment and its connection to the main river.

The restoration project was authorized by the U.S. Congress in 1992, in partnership with the South Florida Water Management District and the U.S. Army Corps of Engineers. The general plan for the restoration is shown in Figure 4.D.

The restoration of the Kissimmee River is an ongoing project that began several years ago. By 2001, approximately 12 km of the nearly straight channel had been restored to a meandering channel with floodplain wetlands about 24 km long. This returned the ecosystems to a more natural state as water again flowed through a meandering channel and onto the floodplain. As a result, wetland vegetation was reestablished, and birds and other wildlife are returning. The potential flood hazard is being addressed as the restoration plans allow the river to meander through its floodplain while maintaining flood protection. Retaining flood protection is the reason the entire river will not be returned to what it was prior to channelization; that is, some of the structures that control the floodwaters will be removed and others will be maintained.

The cost of restoring the Kissimmee River will be several times greater than the cost of channelizing it. However, the project reflects our values in maintaining biological diversity and providing for recreational activities in a more natural environment.

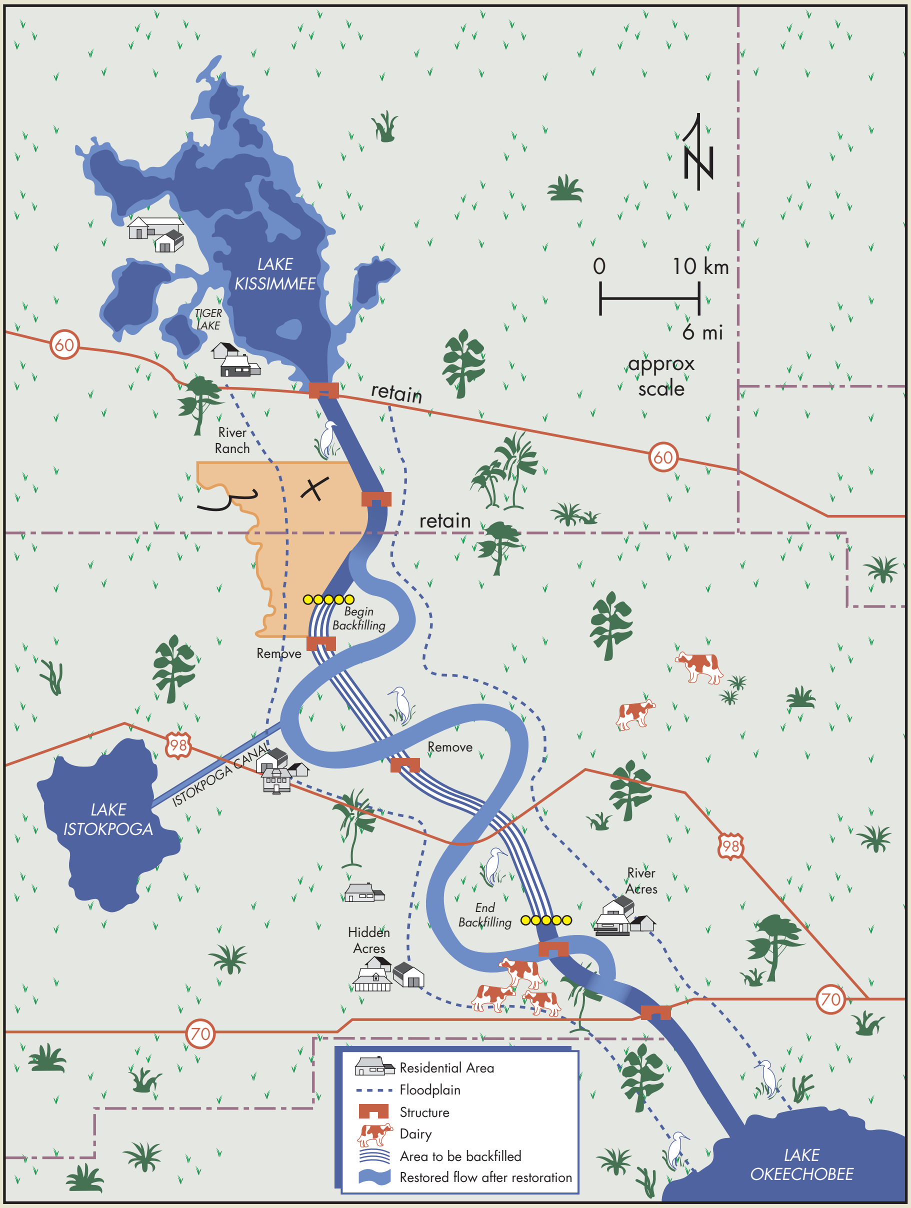


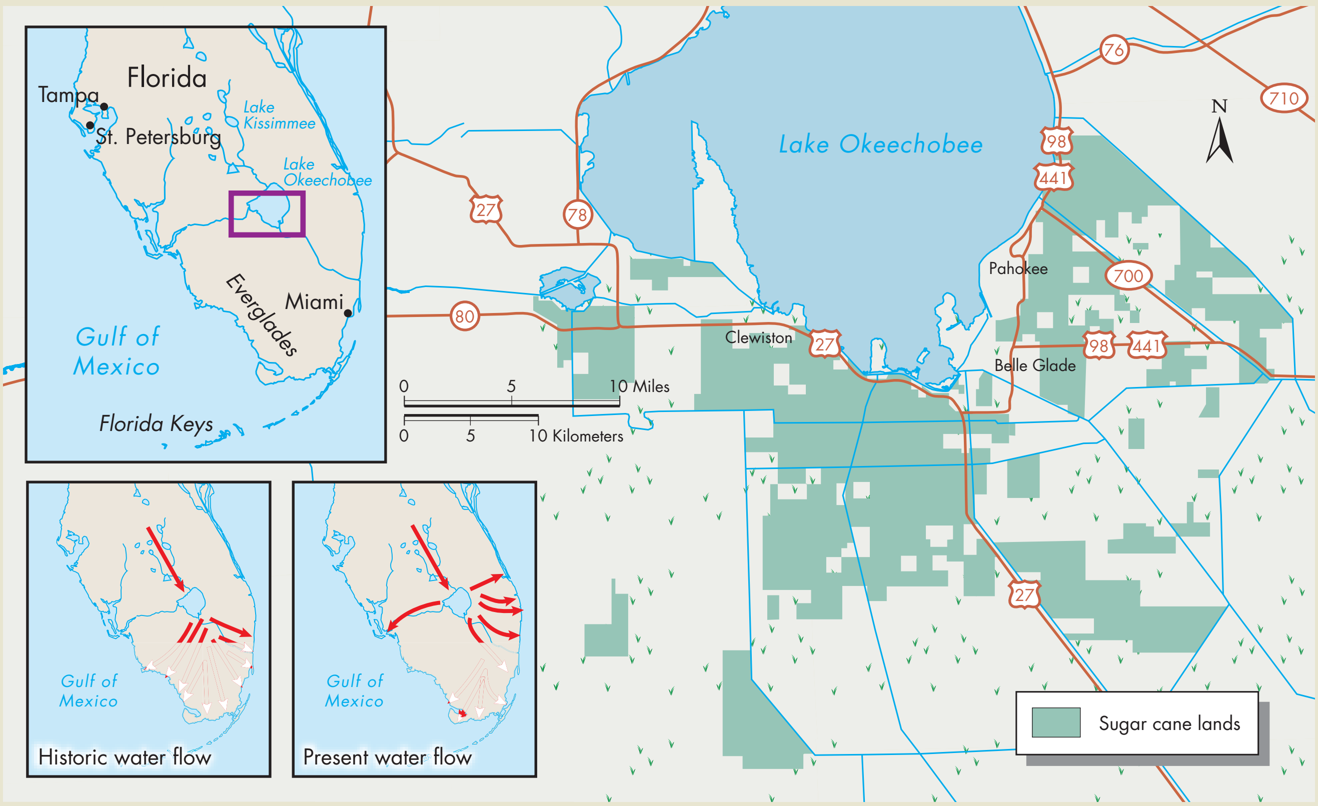
FIGURE 4.D Kissimmee River restoration plan General plan for restoration of the Kissimmee River. One of the major objectives is to restore biological diversity in ecosystem function of the river, as well as re-create the historic river floodplain environment that is connected to the main river. *(South Florida Water Management District)*

A Closer Look

Restoration of the Florida Everglades

The Florida Everglades is considered to be one of the nation's most valuable ecological treasures. The ecosystems of the Everglades stretch from a series of small lakes near Orlando, Florida, southward to Florida Bay for a length of several hundred kilometers (**Figure 4.E**). The area north of Lake Okeechobee comprises the drainage area feeding into the lake, while the area south of the lake is a long system of wetlands that may be hydrologically described as a shallow, wide body of slowly moving water. Tourists from around the world have visited the Everglades for generations. They come to see the unique landscape, as well as the wildlife. The Everglades is home to more than 11,000 species of plants, as well as several hundred bird species and numerous species of fish and marine mammals, including the endangered Florida manatee. The wetlands and surrounding areas are the last remaining habitat for nearly 70 threatened or endangered species, including the Florida panther and the American crocodile. Since about 1900, much of the Everglades has been drained for agriculture and urban developments, and only 50 percent of the original wetlands remain. A complex system of canals and levees controls much of the flow of water for a variety of purposes, including flood control, water supply, and land drainage.

Over many decades, the draining of the wetlands and the encroachment of urban areas have degraded the ecosystem of the Everglades to the point where the resource was likely to



(a)

FIGURE 4.E Florida Everglades (a) Maps of Florida, showing the Everglades in southernmost Florida. The Everglades is a wide, shallow, flowing river-like system extending from Lake Okeechobee south to the Atlantic Ocean. Notice the historic flow of water has been changed, particularly south of Lake Okeechobee where sugar cane is abundant. *(Modified from data and maps from the South Florida Water Management District)* (b) The Florida Everglades includes several diverse ecosystems including sawgrass marshes (shown here), cyprus swamps, estuarine mungroves, and many islands with hardwood and pine trees. *(Eric Foltz/iStockphoto)*

(b)

be lost unless a restoration program was implemented. That restoration is now underway, and it is the largest environmental project in a wetland in the world. The program is a 30-year endeavor that will cost upwards of $10 billion. Restoration goals[10] include:

- Restoration of more natural hydrologic processes.
- Enhancement and recovery of native and, particularly, endangered species.
- Improvement of water quality, especially control of nutrients from agricultural and urban areas.
- Restoration of habitat for all wildlife that use the Everglades.

The restoration plan is an aggressive one that involves federal, state, and tribal partners, as well as numerous other groups interested in the Everglades. The progress to date is notable, as pollution of water flowing into the Everglades from agricultural activities has been reduced by about one-half. As a result, the water entering the system is cleaner than it has been for years. In addition, thousands of hectares have been treated to remove invasive, exotic species, such as Brazilian pepper trees and tilapia (a fish from Africa), with the objective of improving and conserving habitat for a variety of endangered and other species.

The plan to restore the Everglades is a long-term one and involves many years of scientific research yet to be completed. The program is complicated by the fact that more than 5 million people live in south Florida. The area has a rapidly growing economy, and many urban issues related to water quality and land use need to be addressed. Perhaps the biggest issue is the water, and the plan will need to carefully consider restoration that delivers the water in the proper amount, quantity, and place to support ecosystems in the Everglades. This will be a challenge because millions of people in south Florida are also competing for the water.

The overriding goal of the restoration is to ensure the long-term sustainability of water resources in the ecosystem of the Everglades.[10] Doing this includes:

- Controlling the human population in south Florida, controlling human access to the Everglades, and controlling human development that encroaches on the Everglades
- Applying the principle of environmental unity (everything affects everything else; see Chapter 1) to better understand and anticipate possible consequences resulting from changes to the geologic, hydrologic, and ecological parts of the system
- Applying the precautionary principle (see Chapter 1)
- Analyzing rates and changes of systems related to the water, land, and wildlife, as linked to people

It is clear that the people of south Florida and the nation value the ecosystem of the Everglades and are applying science with values to implement a far-reaching ecological restoration program. Hopefully, it will be successful, and future generations will look back to this point in time as a "watershed" (poor pun) that started the ball rolling to protect one of the most valuable ecological resources in North America.

cycle, referring to surface waters and groundwater. Soils and rocks include the microorganisms that reside in the soil. Vegetation is the cover material on land and in wetland ecosystems. When we apply the Big Three in a restoration project, we soon realize that ecological restoration, as it is applied today, is part art and part applied science. This is because we do not often know enough about particular ecosystems to define their function, structure, and process accurately. Ecological restoration also has a

A Closer Look

Coastal Sand Dune Restoration at Pocket Beaches: University of California, Santa Barbara

The University of California, Santa Barbara, has several kilometers of beach on its campus. Two small pocket beaches exist at locations where the sea cliff is interrupted or cut through by prehistoric channels. At these locations, some sand blows from the beaches inland for several tens of meters, and a series of low coastal sand dunes have developed. Over the years, the dunes were colonized by a South African species of ice plant. The ice plant came to cover the entire dune, inhibiting normal dune function by allowing no other plants to grow and inhibiting natural sand movement. As a result, the biodiversity of the dune ecosystem was greatly reduced. Restoration of the dunes has involved solarizing the ice plant. This is done by covering the plants with black plastic for several months, until they die and turn into mulch. The dune is then planted with native dune species (**Figure 4.F**). As native vegetation returns to the dunes, the ecosystem is restored. The restoration of the dunes was simple and straightforward, with limited objectives of removing exotic, invasive species and replacing them with native species. When this was done, the function of the ecosystem recovered, and biological diversity increased. In this case, the restoration of composition (i.e., plants) promotes the restoration of process (i.e., allows the sand in the dunes to move). However, in the Everglades and Kissimmee River examples, hydrologic processes need to be restored prior to restoring composition.

FIGURE 4.F Sand dune restoration Sand dunes at the University of California, Santa Barbara, following restoration. The invasive species (ice plant) has been removed and native dunes species have been planted. Before restoration the dunes look like large mounds of ice plants. *(Edward A. Keller)*

component of societal contribution that goes along with the scientific contribution. In this respect, restoration is a social activity. The contribution from people in communities where restoration will take place, or as they are sometimes called, the *stakeholders*, is important in establishing goals for restoration. A series of public meetings for comment and recommendations are held prior to starting restoration projects. There is feedback between the goals and scientific endpoints, which are a consequence of the goals. For example, if we are restoring a salt marsh and want the plants in the marsh to reduce the nutrient loading to a particular level, then that level is a scientific endpoint. If it turns out that the endpoint may not be reached, then further consideration of goals may be in order. The scientific

measures refer to the measurements and monitoring that happen along the way toward achievement of scientific endpoints and the goals of the restoration. The contribution of science is important in developing the endpoints and measures. Good restoration applies the principle of *adaptive management,* which is the flexible process of improving management policy and plans through learning from past experience with a project. With adaptive management, science is used as an integral part of restoration projects from initial project evaluation through implementation and post-project monitoring.

Ecological restoration efforts may vary—from very simple procedures, such as removing exotic species of plants and planting desired species, with a focus on the restoration of composition and structure, to reconstruction of the entire landscape, with a focus on process. Reconstruction of a landscape and its ecosystems requires intimate knowledge of geologic and hydrologic processes. **Table 4.1** lists details of the processes of restoration.

Regardless of the nature and extent of the restoration being done, it is a negotiated process between people interested in the project, those doing the restoration, and scientists making recommendations, gathering data, and analyzing results. It is also important to recognize that evaluation of a restoration project starts long before construction. This evaluation involves identifying environmentally sensitive aspects of the project and how they might interact with important historic or cultural values. Prior to construction, a careful evaluation of the geologic, hydrologic, and vegetation conditions at the site is necessary to match the environment to the restoration procedures. In other words, we evaluate the hydrology, geology, and vegetation in terms of the overall goals of the project and what is being restored. During restoration, monitoring is often necessary to help evaluate whether the objectives are being achieved. Also, during the entire project, including the development of goals, those doing the restoration should work closely with the community people involved, including environmentalists, property owners, and other interest groups, to maximize opportunities to cooperate in the restoration project. Finally, it's important to recognize that ecological restoration, while often successful, is likely to have mixed success. This is particularly likely in the first years of a restoration project, when unexpected difficulties often occur, making changes in the restoration plan necessary. There may also be natural events, such as droughts or severe storms, that will interfere with the restoration activities.

TABLE 4.1 Steps and Procedures in Planning and Initiating an Ecological Restoration Project

1. Develop an ecological description of the area to be restored.
2. Provide a clear understanding of the need for the restoration.
3. Define the objectives and goals of the project.
4. Specifically state the procedures that will be used to achieve the restoration.
5. Clearly know the reference ecosystem that the restoration is attempting to reach.
6. Determine how the restored ecosystem will be self-sustaining; that is, provide for flow of energy and cycling of chemicals to ensure long-term self-maintenance of the restored ecosystem and stable linkages to other ecosystems.
7. State the standards of performance during restoration and monitoring following completion.
8. Work with all people interested in the project (stakeholders) from initiation through completion and postproject monitoring.
9. Examine what the potential consequences of the project are likely to be; that is, apply the principle of environmental unity, that everything affects everything else and anticipate what primary, secondary, and tertiary effects may be.

Modified after Society for Ecological Restoration, 2004. *The SER International Primer on Ecological Restoration,* www.SER.org.

Another concept related to ecological restoration is *biological engineering*, which is the use of vegetation in engineering projects to achieve specific goals such as protecting stream banks from erosion.[7,8] On a broader scale, ecological engineering includes designing and constructing ecosystems.

Making The Connection

Linking the Opening Case History About Endangered Southern Steelhead Trout to the Fundamental Concepts

Consider and discuss the following questions:

1. Why do you think that southern steelhead trout in California are endangered? How might their populations be stabilized or recover (i.e., increase)?
2. What might be the role of increasing human population and science/values in the recovery of an endangered species, such as southern steelhead trout?
3. What does knowledge of geologic and hydrologic systems contribute to understanding how ecosystems function in general and, specifically, ecosystems that include southern steelhead?

Summary

Ecology is the study of living things and their interactions and linkages to each other and their nonliving environment. It can also be viewed as the study of factors influencing the distribution and abundance of species. An ecosystem is a community of organisms and their interactions with the nonliving environment in which energy flows and chemicals cycle. Therefore, understanding ecosystems involves understanding the geologic, biogeochemical, and hydrologic environment.

Geology has many linkages to biodiversity through its influence on the abundance and distribution of plants and animals. Examples include trout habitat in southern California, the forests of North America and Europe, wolves and elk in Yellowstone National Park and their relationship to stream processes, and the kelp forest in California related to the interaction of sea otters and the urchins they eat.

Human activity and interest dominate almost all ecosystems on Earth. Our processes (influences) are reducing biodiversity, including the loss of entire ecosystems and the extinction of many species. The processes of most concern are land transformation, such as transformation of the land from a natural environment to agriculture or urban uses, introduction of invasive species, processes that cause global change, and change to biogeochemical cycles. Reducing the human footprint on the ecosystems of Earth is an important objective and will include, among other activities, controlling human population, managing Earth's resources for sustainability, and managing our waste more efficiently.

We are in need of an appropriate environmental ethic based on a time scale of interest to people. If we choose to sustain resources and ecosystems, we will have a more compatible relationship with our home (Earth), and our species will be able to remain on the planet a bit longer.

Ecological restoration is emerging as an important process with a variety of goals and objectives. In general, ecological restoration has the purpose of reestablishing sustainable ecosystem structure, process, and function.

Revisiting Fundamental Concepts

Human Population Growth

Controlling human population growth is an important objective in sustaining our environment and reducing the human footprint on the environment. If we are unable to control human growth, we will have little success in achieving sustainable management of our resources.

Sustainability Sustainability is the environmental objective. Sustaining Earth's ecosystems is necessary if we hope to sustain our human system. We share our planet with a vast number of other living things, and many of these are necessary for our own well-being. Therefore, when we consider geology and ecosystems, we need to consider those linkages that will lead to sustainable development in its broadest context.

Earth as a System Ecosystems are an important component of Earth systems that link living organisms with their nonliving environment. Geologic and hydrologic systems have simple to complex relationships with communities of organisms. These organisms have important linkages to the diversity of living organisms in ecosystems. Maintaining living systems in a desired and sustainable state must involve understanding the role of geologic and hydrologic processes and maintaining these processes in a way that supports the desired biological conditions.

Hazardous Earth Processes, Risk Assessment, and Perception Ecosystems have natural service functions that are linked to hazards, such as landslides and flooding. Bank vegetation on stream banks increases the stability of stream banks and their resistance to erosion. Wetlands moderate floodwater by storing and releasing it slowly, thus reducing flood hazards. Wetlands provide a buffer to storm waves from the ocean and, thus, help protect coastal areas from erosion and flooding.

Scientific Knowledge and Values The science of ecology has provided a lot of information about ecosystems. How we use that knowledge to restore and maintain ecosystems will reflect our values.

Key Terms

biodiversity (p. 115)
ecological restoration (p. 126)
ecology (p. 112)
ecosystem (p. 114)

Review Questions

1. Define *ecosystem*.
2. What is the relationship between a species and an ecological community?
3. What is meant by biodiversity?
4. What factors may increase or decrease biodiversity?
5. What did you learn from the case histories of wolves in Yellowstone National Park and sea otters in the kelp forest of southern California?
6. How do seawalls reduce biodiversity?
7. What is meant by the golden rule of the environment?
8. What is ecological restoration?
9. What is the difference between ecological restoration, naturalization, and biological engineering?
10. What are some important linkages between geology and ecology?

Critical Thinking Questions

1. An ecosystem consists of an ecological community and its nonliving environment. Which of the two do you think is more important and why? In other words, do you think the physical environment comes before what lives there, or does what lives there affect the physical environment to a greater extent than the role of geology? Or are both things equally important?
2. Visit a local stream. Carefully examine the stream and surrounding environment and try to determine the amount of human domination. Is the stream you are looking at a candidate for restoration? If so, what could be done? If it's not a candidate for restoration, why not?
3. Why may some geologists and hydrologists not be particularly aware of ecosystem function in terms of the biological environment? Why are some biologists unaware of the details of the physical and hydrologic conditions of the ecosystems they work with? What can be done to narrow the gap between those working on living systems and those working on geologic or hydrologic systems?

Companion Website

www.mygeoscienceplace.com

Introduction to Environmental Geology, *5e* premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

This page intentionally left blank

Part 2

Earth Processes and Natural Hazards

Our focus in Part 2 turns to the major natural hazards: an introduction to hazardous processes (Chapter 5); earthquakes (Chapter 6); tsunami (Chapter 7); volcanic activity (Chapter 8); flooding (Chapter 9); landslides (Chapter 10); coastal processes, including hurricanes (Chapter 11); and impacts of asteroids and comets (Chapter 12). The purpose is not to provide extensive amounts of detailed information concerning these natural processes that we define as hazards but to focus on the basics involved and the environmental concerns resulting from interactions between people and natural processes and hazards.

The major principles presented are these: (1) Earth is a dynamic environment, and change resulting from natural processes is the norm rather than an exception; (2) we must strive to learn all we can about natural processes and hazards so that effects on human society may be minimized; and (3) human population increase and changing land use are greatly increasing the threat of loss of life and property to natural hazards. Of particular importance is the recognition of locations where hazardous processes are going to occur and their natural or human-induced return period (i.e., time between events). We will learn that the environmentally preferred adjustment to natural hazards is environmental planning to avoid those locations where the hazards are most likely to occur and to zone the land appropriately. Environmental planning involves detailed study of natural processes and mapping of those processes to produce environmental maps that are useful in the planning process.

Hurricane Katrina, a giant storm This aerial image shows Hurricane Katrina approaching the New Orleans region. (*NOAA*)

5

Introduction to Natural Hazards

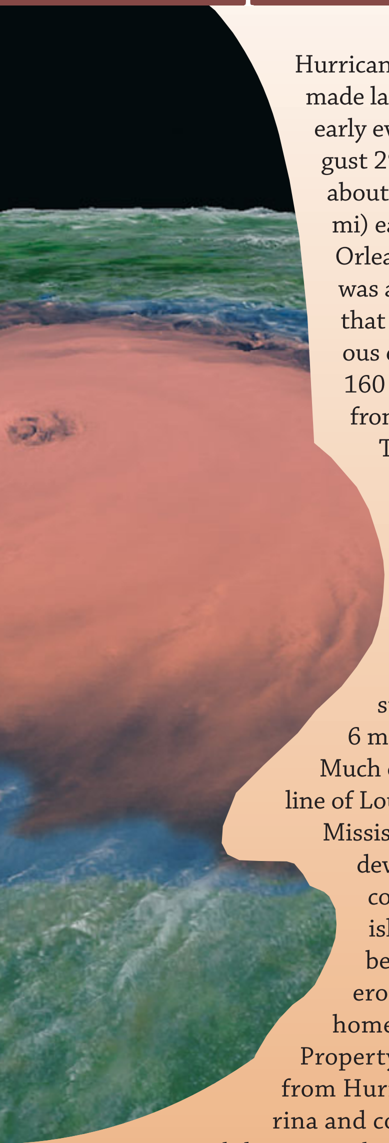
Learning Objectives

Natural hazards are naturally occurring processes that may be dangerous to human life and structures. Volcanic eruptions, earthquakes, floods, and hurricanes are all examples of natural hazards. Human population continues to increase, and there is a need to develop environmentally sound strategies to minimize the loss of life and property damage from hazards, especially in urban areas. The study of hazardous processes, therefore, constitutes one of the main activities of environmental geology. The learning objectives for this chapter are:

- **Understand why increasing population and changing land use increase the threat of loss of life and property from a natural disaster to the level of a catastrophe**
- **Know the conditions that make some natural Earth processes hazardous to people**
- **Understand how a natural process that gives rise to disasters may also be beneficial to people**
- **Understand the various natural processes that constitute hazards to people and property**
- **Know why history, linkages between processes, prediction, and risk assessment are important in determining the threat from natural hazards**
- **Know how people perceive and adjust to potential natural hazards**
- **Know the stages of recovery following natural disasters and catastrophes**

Case History

Hurricane Katrina, the Most Serious Natural Catastrophe in U.S. History



Hurricane Katrina made landfall in the early evening of August 29, 2005, about 45 km (30 mi) east of New Orleans. Katrina was a huge storm that caused serious damage up to 160 km (100 mi) from its center. The storm produced a storm surge (i.e., a mound of water pushed onshore by the storm) of 3 to 6 m (9 to 20 ft). Much of the coast line of Louisiana and Mississippi was devastated as coastal barrier islands and beaches were eroded and homes destroyed. Property damage from Hurricane Katrina and costs to rehabilitate or rebuild the area may exceed $100 billion, making it the most costly hurricane in the history of the United States. The number of human deaths will never be known for sure, as many bodies may have been washed out to sea or buried too deep to be found. The official number of deaths is 1,836. The hurricane and subsequent flooding set into motion a series of events that caused significant environmental consequences. Initial loss of life and property from wind damage and storm surge was immense. Entire coastal communities disappeared, along with their fishing industries.

At first it was thought that the city of New Orleans had been spared, as the hurricane did not make a direct hit. The situation turned into a catastrophe when water from Lake Pontchartrain, north of the city and connected to the Gulf of Mexico, flooded the city. Levees capped with walls, constructed to keep the water in the lake and protect low-lying parts of the city, collapsed in two locations, and water poured in. Another levee failed on the Gulf side of the city and contributed to the flooding. Approximately 80 percent of New Orleans was under water from knee deep to rooftop depths or greater (**Figure 5.1**). People who could have evacuated but didn't and those who couldn't because they lacked transportation took the brunt of the storm. A part of the city that wasn't flooded was the French Quarter (Old Town), which is the area of New Orleans famous for music and Mardi Gras.

The people who built New Orleans over 200 years ago realized that much of the area was low in elevation and built on the natural levees of the Mississippi River. The natural levees were formed by periodic overbank deposition of sediment from the river over thousands of years. They are parallel to the river channel and are higher than the adjacent land, providing natural flood protection. As marshes and swamps were drained in lower areas, the city expanded into low areas with much greater flood hazard. Much of the city is in a natural bowl, and parts are 1 to 3 m (3 to 9 ft) below sea level (**Figure 5.2**).

It has been known for a long time that if a large hurricane were to make a direct or near-direct hit on the city, extensive flooding and losses would result. The warnings were not completely ignored, but sufficient funds were not forthcoming to maintain the levees and system of floodwalls to protect low-lying areas of the city from a large hurricane.

The fact that the region is subsiding at highly variable rates from 1 to 4 m (3 to 12 ft) per 100 years contributed to the flood hazard. Over short periods, 50 percent to 75 percent of the subsidence in some areas is natural, resulting from geologic processes

FIGURE 5.1 Katrina floods New Orleans New Orleans was flooded when flood defenses failed during Hurricane Katrina. *(N. Smiley/Pool/Dallas Morning News/Corbis)*

FIGURE 5.2 Map and cross section of New Orleans Much of the city is below sea level between the Mississippi River and Lake Pontchartrain. *(Edward A. Keller)*

(i.e., movement along faults) that formed the Gulf of Mexico and the Mississippi River delta.[1] As much as several meters (more than 10 ft) of subsidence has occurred in the past 100 years, and, during that period, sea level has risen about 20 cm (8 in.). The rise is due in part to global warming. As the Gulf water and ocean water warm, they expand, raising sea level. The subsidence results in part from a number of human processes, including extraction of groundwater, oil, and gas, as well as loss of freshwater wetlands that compact and sink when denied sediment from the Mississippi River. Because the Mississippi River has artificial levees (i.e., embankments constructed by humans), it no longer delivers sediment to the wetlands. Therefore, wetlands have stopped building up from sediment accumulation. Before the levees were constructed in the Mississippi River delta, floodwater with its sediment spread across the delta, helping maintain wetland soils and plants. The freshwater wetlands near New Orleans were largely removed during past decades. As wetlands are removed, they are replaced by saltwater ecosystems as sea level rises and the land continues to subside. The freshwater wetlands are a better buffer to winds and storm waves than are saltwater wetlands. Tall trees, such as cypress and other plants of freshwater wetlands (Figure 5.3), provide roughness that slows down water from high waves or storm surge moving inland. It's well known that one of the natural service functions of both saltwater and freshwater coastal wetlands is to provide protection to inland areas from storms.

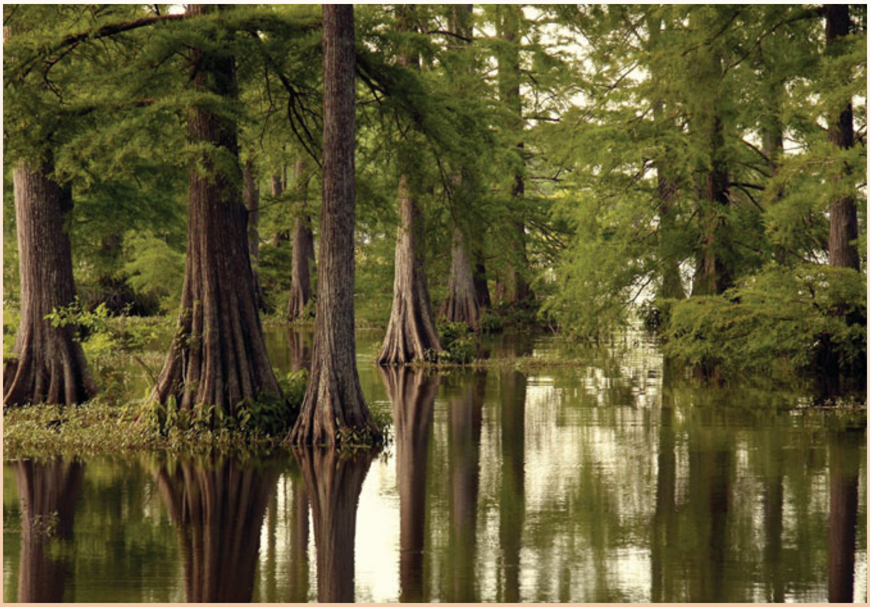


FIGURE 5.3 Cypress tree Freshwater wetlands along the coast of Louisiana have significant ecological importance and help protect the coast from wind and large waves from storms. *(Kristine Carrier/iStockphoto)*

New Orleans Will Be Rebuilt. The people of New Orleans are resilient and are moving (in some cases slowly) back into this famous historic city. We have learned from this event, and better measures are being taken to ensure that this kind of catastrophe is less likely to occur in the future. For example, in some areas where floodwaters, even with future levee failure, will be less than one story high, reconstruction includes flood-proof buildings with living areas on the second floor.

The U.S. Army Corps of Engineers, which is largely responsible for the

5.1 Hazards, Disasters, and Natural Processes

On a world scale, the occurrences of natural disasters such as floods, earthquakes, volcanic eruptions, and landslides are increasing. Several criteria used to define a **natural disaster** are: 10 or more people are killed, 100 or more people are affected, a declaration of emergency is issued, and a request is made for international assistance. If any one of these criteria applies, a particular event is considered to be a natural disaster.[3] The increase in the number of disasters is, in part, due to better reporting, but there are other factors as well:[4]

- Increases in human population and urbanization are putting more people in places where natural processes may produce disasters for people. These include regions along the coast where erosion or tsunami may occur and along active faults, near volcanoes, or in flood-prone areas. Poverty in urban regions further increases the chances of disaster, as poor people are often pushed into the most hazardous areas on floodplains or steep slopes.

flood protection of New Orleans, produced a draft report in June 2006 concerning the hurricane- and flood-protection system. It acknowledged that the system had evolved piecemeal over a number of decades and that it was a system in name only. Nevertheless, the flood-protection structures were constructed to protect the city, and their failure was responsible for a majority of the flooding that resulted from Hurricane Katrina in 2005.

The U.S. Army Corps of Engineers reached the following conclusions:[2]

- There were no fallback redundancies (i.e., there was no second-tier protection) to the flood protection if the primary flood-control structures failed. Pumping stations designed to remove floodwaters were the only example of a redundant system, and they were not designed to function in a major hurricane with extensive flooding.
- Hurricane Katrina exceeded the design criteria of the flood-protection structures. Some levee and floodwall failures resulted from being overtopped by floodwaters. Others failed, without being overtopped, due to erosion from their front side.
- Regional subsidence has been faster than was appreciated. The heights of the flood-protection structures were not adjusted for subsidence, and some of the floodwalls and levees were as much as 1 m (3 ft) below the elevation at which they were designed.
- Although scientific knowledge about hurricanes and storm surges has increased, this did not lead to updating the flood-control plan. What adjustment did occur was fragmented rather than consistent and uniform.
- Consequences of flooding were also concentrated. More than 75 percent of the people who died were over 60 years old and were located in areas with the greatest depth of flooding. The larger number of deaths among the elderly occurred because poor, elderly people and disabled people were the least able to evacuate without assistance.
- Parts of the flood- and hurricane-protection system have been repaired at a cost of about $800 million since Katrina, and these are the strongest parts of the flood protection. At present, however, the protection level remains the same as before Katrina.

In fairness to the Army Corps of Engineers, flood-control structures are often underfunded, and, as with New Orleans, construction is spread over many years. Hopefully, we have learned from Katrina and will build a stronger, more effective hurricane-protection system for the city of New Orleans, as well as other U.S. cities where hurricanes are likely to occur.

Can flooding occur again in New Orleans, even if higher, stronger flood defenses are constructed? Of course it can; when a bigger storm strikes, future damage is inevitable. If freshwater marshes are restored and the river waters of the Mississippi are allowed to flow through them again, they will help provide a buffer from winds and waves. As previously mentioned, freshwater marshes have trees that provide a roughness to the land that slows wind and retards the advance of waves from the Gulf. Every 1.5 km (1 mi) of marsh land can reduce waves by about 25 cm (1 ft).

Tremendous amounts of money will need to be spent to make New Orleans more resistant to storms in the future. In light of the many billions of dollars in damages from catastrophes, it seems prudent to spend the money in a proactive way to protect important resources, particularly in our major cities.

In the remainder of this chapter, we will discuss some of the principles of natural processes we know as hazards and how they produce disasters and catastrophes. You will learn how poor land uses and changing land uses, coupled with population increase, greatly increase the risk of some hazards.

- Environmental damage to the land, such as deforestation, linked to poor land use choices increases the frequency and potential sites of natural hazards, such as flooding and landsliding. Removal of coastal wetlands and other vegetation renders the coast more vulnerable to wave erosion from tsunami and other storms.
- Climate change linked to rising sea level increases coastal erosion. As the planet warms, deserts expand, increasing the occurrence of hazardous dust storms. Warming oceans allow more energy to be transferred to the atmosphere, influencing the intensity of damaging storms.

Natural Disasters: Loss of Life and Property Damages

Natural disasters are events that cause great loss of life or property damage—or both—such as earthquakes, floods, and cyclones (hurricanes). Natural disasters have in the past few decades killed several million people, with an average worldwide annual loss of life of about 150,000 people. The financial losses resulting from natural disasters now exceed $50 billion per year and do not include social impacts, such as loss of employment, mental anguish, and reduced productivity. Four individual disasters—a cyclone

accompanied by flooding in Bangladesh in 1970, an earthquake in China in 1976, a tsunami in the Indian Ocean in 2004 and an earthquake in Haiti in 2010—each claimed about 250,000 lives. These terrible disasters (catastrophes) were caused by natural hazards that have always existed—atmospheric disturbance and tectonic movement—but their extent was affected by human population density and land use patterns.

Why Natural Processes Are Sometimes Hazards

Natural hazards are basically natural processes. These processes become hazardous when people live or work in areas where they occur. Natural processes can also become hazardous when land-use changes, such as urbanization or deforestation, affect natural processes, causing flooding or landsliding. It is the environmental geologist's role to identify potentially hazardous processes and make this information available to planners and decision makers, so that they can formulate various alternatives to avoid or minimize the threat to human life or property. However, the naturalness of hazards is a philosophical barrier that we encounter whenever we try to minimize their adverse effects. For example, we try to educate people that a river and floodplain, the flat land adjacent to the river, are part of the same natural system and that we should expect floods on floodplains, as the name suggests. Minimizing the flood hazard may be as simple as not building on floodplains! However, this seemingly logical solution is difficult to get across to people who see floodplains as flat land on which to build houses.

Magnitude and Frequency

The *impact* of a disastrous event is in part a function of its *magnitude*, or the amount of energy released, and *frequency*, or recurrence interval; however, it is influenced by many other factors, including climate, geology, vegetation, population, and land use. In general, the frequency of a disastrous event is inversely related to the magnitude. Small earthquakes, for example, occur more often than do large ones (see A Closer Look: The Magnitude–Frequency Concept).

Benefits of Natural Hazards

It is ironic that the same natural events that take human life and destroy property also provide important benefits, or natural service functions. For example, periodic flooding of the Mississippi River supplies nutrients to the floodplain, forming the fertile soils used for farming. Flooding, which causes erosion on mountain slopes, also delivers river sediment to beaches (**Figure 5.4**) and flushes pollutants from estuaries in the coastal environment. Landslides may bring benefits to people when landslide debris forms dams, creating lakes in

(a)

(b)

FIGURE 5.4 Dams and beaches (a) Sediment from the Ventura River in southern California is delivering some sand to beaches in the region; however, an old upstream dam (b) is storing sand that might otherwise nourish the beach. The dam is scheduled to be removed. *([a] Pacific Western; [b] Edward A. Keller)*

A Closer Look

The Magnitude–Frequency Concept

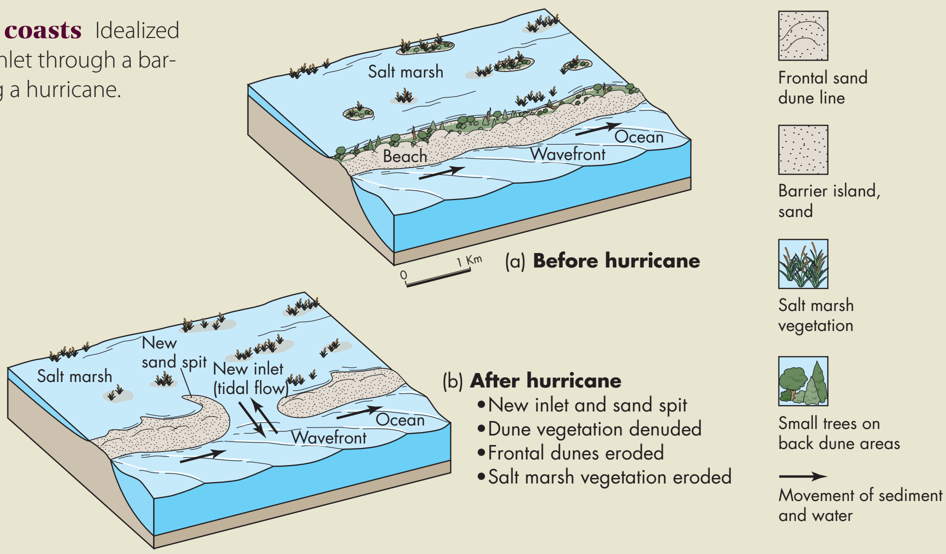
The **magnitude–frequency concept** states that there is generally an inverse relationship between the magnitude of an event and its frequency. For example, the larger a flood, the less frequently such a flood occurs. The concept also includes the idea that much of the work of forming Earth's surface occurs through events of moderate magnitude and frequency rather than through common natural processes of low magnitude and high frequency or through extreme events of high magnitude and low frequency.

As an analogy to the magnitude–frequency concept, consider the work of reducing the extent of a forest by resident termites, human loggers, and elephants (Figure 5.A). The termites are numerous and work quite steadily, but they are so small that they can never do enough work to destroy all the trees. The people are fewer and work less often, but, being stronger than termites, they can accomplish more work in a given time. Unlike the termites, the people can eventually fell most of the trees. The elephants are stronger still and can knock down many trees in a short time, but there are only a few of them, and they rarely visit the forest. In the long run, the elephants do less work than the people and bring about less change.

In our analogy, it is humans who, with a moderate expenditure of energy and time, do the most work and change the forest most drastically. Similarly, natural events with moderate energy expenditure and moderate frequency are often the most important shapers of the landscape. For example, most of the sediment carried by rivers in regions within a subhumid climate (most of the eastern United States) is transported by flows of moderate magnitude and frequency. However, there are many exceptions. In arid regions, for example, much of the sediment in normally dry channels may be transported by rare high-magnitude flows produced by intense but infrequent rainstorms. Along the barrier-island coasts of the eastern United States, high-magnitude storms often cut inlets that cause major changes in the pattern and flow of sediment (Figure 5.B).

FIGURE 5.A Human scale of change Human beings, with their high technology, are able to down even the largest trees in our old-growth forests. The lumberjack shown here is working in a national forest in the Pacific Northwest. *(William Campbell/Corbis)*

FIGURE 5.B Hurricanes change coasts Idealized diagram showing the formation of an inlet through a barrier island resulting from erosion during a hurricane. (a) Before and (b) after hurricane.



mountainous areas (**Figure 5.5**). Although some landslide-created dams collapse and cause hazardous downstream flooding, dams that remain stable can provide valuable water storage and are an important aesthetic resource.

Volcanic eruptions have the potential to produce catastrophes; however, they also provide numerous benefits. They often create new land, as in the case of the Hawaiian Islands, which are completely volcanic in origin (**Figure 5.6**). Nutrient-rich volcanic ash may settle on existing soils and may quickly become incorporated, creating soil suitable for wild plants and crops. Earthquakes can also provide us with valuable services. When rocks are pulverized during an earthquake, they may form an impervious clay zone known as *fault gouge* along the fault. In many places, fault gouge has formed groundwater barriers upslope from a fault, producing natural subsurface dams and water resources. Along some parts of the San Andreas fault in the arid Coachella Valley near Indio, California, this process has produced oases, in which pools of water are surrounded by native palm trees in an otherwise desert environment (**Figure 5.7**). In addition, earthquakes are also important in mountain building and, thus, are directly responsible for many of the scenic resources of the western United States.

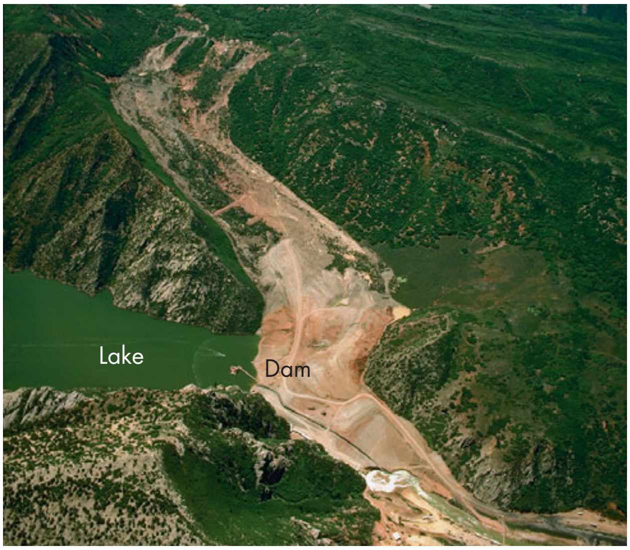


FIGURE 5.5 Landslide dam This landslide dam in Utah is forming a lake. *(Michael Collier)*

Death and Damage Caused by Natural Hazards

When we compare the effects of various natural hazards, we find that those that cause the greatest loss of human life are not necessarily the same ones that cause the most extensive property damage. **Table 5.1** summarizes selected information about the effects

(a)

(b)

FIGURE 5.6 New land from volcanic eruption New land being added to the island of Hawaii. (a) The plume of smoke in the central part of the photograph is where hot lava is entering the sea. (b) Close-up of an advancing lava front near the smoke plume. *(Edward A. Keller)*

(a) (b)

FIGURE 5.7 Oases and faults (a) Native palm trees along the San Andreas fault, Coachella Valley, California. The fault dams groundwater that the trees use. (b) In some cases, the water forms surface pools and oases. *(Edward A. Keller)*

TABLE 5.1 Effects of Selected Hazards in the United States

Hazard	No. of Deaths per Year	Occurrence Influenced by Human Use	Catastrophe Potential[2]
Flood	86	Yes	H
Earthquake[1]	50 + ?	Yes	H
Landslide	25	Yes	M
Volcano[1]	<1	No	H
Coastal erosion	0	Yes	L
Expansive soils	0	No	L
Hurricane	55	Perhaps	H
Tornado and windstorm	218	Perhaps	H
Lightning	120	Perhaps	L
Drought	0	Perhaps	M
Frost and freeze	0	Yes	L

[1]Estimate based on recent or predicted loss over 150-year period. Actual loss of life and/or property could be much greater.
[2]Catastrophe potential: high (H), medium (M), low (L).
Source: Modified after White, G. F., and Haas, J. E. 1975. *Assessment of research on natural hazards.* Cambridge, MA: MIT Press.

of natural hazards in the United States. The largest number of deaths each year is associated with tornadoes (**Figure 5.8**) and windstorms, although lightning (**Figure 5.9**), floods, and hurricanes also take a heavy toll. Loss of life due to earthquakes can vary considerably from one year to the next, as a single great quake can cause tremendous human loss. It is estimated that a large, damaging earthquake in a densely populated part of California could inflict $100 billion in damages and kill several thousand

FIGURE 5.8 Tornado hazard (a) Tornado in Tampa Bay, Florida, on July 12, 1995. *(Brian Baer/St. Petersburg Times/AP Photo)* (b) Mobile homes destroyed by tornado that struck Benton, Louisiana, on April 4, 1999. *(Eric Gay/AP Photo)*

(a)

(b)

FIGURE 5.9 Lightning strike Lightning is responsible for more than 100 deaths each year in the United States. Shown here are lightning strikes near Walton, Nebraska. *(Martin Fischer/Shutterstock)*

people.[5] The 1994 Northridge earthquake in the Los Angeles area killed approximately 60 people and caused more than $30 billion in property damage. In fact, property damage from individual hazards is considerable. Floods, landslides, frost, and expansive soils each cause mean annual damages in the United States in excess of $1.5 billion. Surprisingly, expansive soils, clay-rich soils that expand and contract with wetting and drying, are some of the most costly hazards, causing over $3 billion in damages annually to building foundations, sidewalks (**Figure 5.10**), driveways, and swimming pools.

An important aspect of all natural hazards is their potential to produce **catastrophes**. A catastrophe is any situation in which the damages to people, property, or society in general are sufficient to make recovery or rehabilitation a long, involved process.[6] Table 5.1 shows the catastrophe potential for the hazards considered. The events most likely to produce catastrophes are floods, hurricanes, tornadoes, earthquakes, volcanic eruptions, and large wildfires (not included in Table 5.1). Landslides, which generally cover a smaller area, have a moderate catastrophe potential. The catastrophe potential of drought is also moderate: Although a drought may cover a wide area and cause high financial losses, there is usually plenty of warning time before its worst effects are experienced. Hazards with low catastrophe potential include coastal erosion, frost, lightning, and expansive soils.

FIGURE 5.10 Soil hazard Organic-rich expansive soils are cracking the walls of this building in Spain. *(Edward A. Keller)*

The effects of natural hazards change with time. Changes in land use patterns that influence people to develop on marginal lands, urbanization that changes the physical properties of Earth materials, and increasing population all alter the effects of natural hazards. Although damage from most hazards in the United States is increasing, the number of deaths from many hazards is decreasing because of better hazard forecasting and warning to the public.

5.2 Evaluating Hazards: History, Linkages, Disaster Prediction, and Risk Assessment

Fundamental Principles Concerning Natural Hazards

The understanding of natural hazards and how we might minimize their impact on people and the environment is facilitated through the recognition of five principles:

1. **Hazards are known from scientific evaluation.** Natural hazards, such as earthquakes, volcanic eruptions, landslides, and floods, are natural processes that can be identified and studied using the scientific method. Most hazardous events and processes can be monitored and mapped, and their future activity can be evaluated based on the frequency of past events, patterns, and types of precursor events.
2. **Risk analysis is an important component in understanding impacts resulting from hazardous processes.** Hazardous processes are amenable to risk analysis based on the probability of an event occurring and the consequences resulting from that event; for example, say that we were to estimate that in any given year in Los Angeles or Seattle, there is a 5 percent chance of a moderate earthquake occurring. If we know the consequence of that earthquake in terms of loss of life and damage, then we can calculate the risk to society of that earthquake actually happening.
3. **Hazards are linked.** Hazardous processes are linked in many ways, from simple to complex. For example, earthquakes can produce landslides and giant sea waves called tsunamis, and hurricanes often cause flooding and erosion.
4. **Hazardous events that previously produced disasters are often now producing catastrophes.** The size of a natural hazardous event, as well as its frequency, is influenced by human activity. As a result of increasing human population and poor land use practices, what used to be disasters are often now catastrophes.

5. **Consequences of hazards can be minimized.** Minimizing the potential adverse consequences and effects of natural hazards requires an integrated approach that includes scientific understanding, land use planning (regulation and engineering), and proactive disaster preparedness.

Role of History in Understanding Hazards

A fundamental principle of understanding natural hazards is that they are repetitive events, and, therefore, studying their history provides much-needed information in any hazard-reduction plan. Whether we are studying flood events, landslides, volcanic eruptions, or earthquakes, the historical and recent geologic history of an area is a primary data set. For example, if we wish to evaluate the flooding history of a particular river, one of the first tasks is to study the previous floods of that river system. This study should include detailed evaluation of aerial photographs and maps, reaching as far back as the record allows. For prehistoric events, we can study the geologic environment for evidence of past floods, such as the sequence of flood deposits on a floodplain. Often, these contain organic material that may be dated to provide a history of prehistoric flood events. This history is then linked with the documented historical record of high flows, providing a perspective on flooding of the river system being evaluated. Similarly, if we are investigating landslides in a particular river valley, studying the documented historical occurrence of these events and linking that information to prehistoric landslides will provide basic data necessary to better predict landslides.

A hydrologist's role in flood analysis is to evaluate streamflow records taken from sites, known as *gauging stations*, where streamflow recorders have been established (**Figure 5.11**). Unfortunately, except with larger rivers, the records are usually relatively short, covering only a few years. Most small streams have no gauging stations. Geologists have the observation skills, tools, and training to "read the landscape." They can evaluate prehistoric evidence for natural hazards and link that information with the modern record to provide the perspective

FIGURE 5.11 Monitoring streamflow This stream gauging station on the Merced River in Yosemite National Park continuously monitors the flow of water in the river. Solar cells provide power. This is not a "run of the mill" station. It is designed to educate park visitors on how streamflow is recorded. *(Edward A. Keller)*

of time on a particular process. Environmental geologists also have the ability to recognize landforms associated with hazardous processes. In addition, they recognize that the nature and extent of a hazard varies as the assemblage of landforms varies. For example, flooding that occurs in a river valley with a flat adjacent floodplain is very different from flooding on a delta. The river and floodplain constitute a relatively simple system, consisting of a single channel bordered by the floodplain (**Figure 5.12**). Deltas, however, are more complex landforms, produced when a river enters a lake or an ocean (**Figure 5.13**). Deltas often have multiple channels that receive floodwaters at various times and places, varying the

FIGURE 5.12 Floodplain Mission Creek, California (left), and floodplain (right) with an urban park on it. The location of the park is an example of good use of a floodplain. *(Edward A. Keller)*

FIGURE 5.13 Delta Nile Delta and surrounding region. Delta and river vegetation are green. The white strips at the delta edge are sandy islands that have had serious erosion problems since the construction of the Aswan Dam (not shown) in 1964. *(Jacques Descloitres/MODIS Rapid Response Team/NASA)*

position of the channel and, thus, the energy of a flood. Processes on deltas are discussed in detail in Chapter 9, but the general principle of the instability of channels associated with different types of landforms is the idea we wish to emphasize here.

In summary, before we can truly understand the nature and extent of a natural hazard, such as flooding at a particular site, we must study in detail the history of the site, especially the occurrence, location, and effects of past floods. Understanding this history provides a perspective on the hazard that allows for the "big picture" to be better understood and appreciated. Integrating historical information with both present conditions and land use change of the recent past, such as deforestation and urbanization, allows for better understanding of the hazard. This results because land use changes can increase the impact of hazards, such as landslides and floods. Studying the record also enables more reliable prediction of future events.

Linkages Between Hazardous Events

Linkages between natural processes that are hazardous to people generally fall into two categories. First, many of the hazards themselves are linked. For example, hurricanes are often associated with flooding, and intense precipitation associated with hurricanes causes coastal erosion and landslides on inland slopes. Natural hazards and the characteristics of Earth materials provide a second type of linkage. For example, the sedimentary rock known as shale is composed of loosely cemented or compacted tiny sediments that are prone to landsliding. Granite provides another example of the linkage between natural hazards and Earth material characteristics. Although generally strong and durable, granite is prone to sliding along fractures within the rock.

Disaster Forecast, Prediction, and Warning

A **prediction** of a hazardous event, such as an earthquake, involves specifying the date, time, and size of the event. This is different from predicting where or how often a particular event, such as a flood, will occur. A **forecast**, on the other hand, has ranges of certainty. The weather forecast for tomorrow may state that there is a 40 percent chance of showers. Learning how to predict or forecast disasters in order to minimize loss of life and property damage is an important endeavor. For each particular hazard, we have a certain amount of information; in some cases, this information allows us to predict or forecast events accurately. When insufficient information is available, the best we can do is to locate areas where disastrous events have occurred and infer where and when similar future events might take place. If we know both the probability and the possible consequences of an event's occurring at a particular location, we can assess the risk the event poses to people and property, even if we cannot accurately predict when it will occur.

The effects of a specific disaster can be reduced if we can forecast or predict the event and issue a warning. In a given situation, most or all of the following elements are involved:

- Identifying the location where a hazardous event will likely occur
- Determining the probability that an event of a given magnitude will occur
- Observing precursor events
- Forecasting or predicting the event
- Warning the public

Location. For the most part, we know *where* a particular kind of event is likely to occur. On a global scale, the major zones for earthquakes and volcanic eruptions have been delineated by mapping earthquake foci and the locations of recent volcanic rocks and volcanoes. On a regional scale, we can predict from past eruptions which areas in the vicinity of certain volcanoes are most likely to be threatened by large mudflows or ash in the event of future eruptions. This risk has been delineated for most large volcanoes, including the Pacific Northwest's Cascade Range and volcanoes in Alaska, Japan, Italy, Mexico, Central and South America, Hawaii, and numerous other volcanic islands in the oceans of the world. On a local scale, detailed work with soils, rocks, and hydrology may identify slopes that are likely to fail and cause a landslide or where expansive soils exist. Certainly, we can predict where flooding is likely to occur from the location of the floodplain and evidence from recent floods, such as the location of flood debris and high-water lines.

Probability of Occurrence. Determining the probability that a particular event will occur in a particular location within a particular time span is

an essential goal of hazard evaluation. For many large rivers, we have sufficient records of flow to develop probability models that can reasonably predict the average number of floods of a given magnitude that will occur in a given time period. Likewise, droughts may be assigned probability on the basis of past occurrence of rainfall in the region. However, these probabilities are similar to the chances of throwing a particular number on a die or drawing an inside straight in poker: The element of chance is always present. For example, a 10 year flood may occur on the average of every 10 years, but it is possible for several floods of this magnitude to occur in any one year, just as it is possible to throw two straight sixes with a die.

Precursor Events. Many hazardous events are preceded by **precursor events**. For example, the surface of the ground may creep, or move slowly down a slope, for a period of time (e.g., days to months) before a landslide. Often, the rate of creep increases up to when the landslide occurs. Volcanoes sometimes swell or bulge before an eruption, and, often, emissions of volcanic gases accompanied by seismic activity significantly increase in local areas surrounding the volcano. Foreshocks and anomalous, or unusual, uplift may precede earthquakes. Precursor events help predict when and where an event is likely to happen. For example, landslide creep or swelling of a volcano may result in the issuance of a warning, allowing people to evacuate a hazardous area.

Forecast. When a forecast of an event is issued, the certainty of the event is given usually as the percentage chance of something happening. When we hear a forecast of a hazardous event, it means we should be prepared for the event.

Prediction. It is sometimes possible to accurately *predict* when certain natural events will occur. Flooding of the Mississippi River, which occurs in the spring in response to snowmelt or very large regional storm systems, is fairly common, and we can often predict when the river will reach a particular flood stage, or water level. When hurricanes are spotted far out to sea and tracked toward shore, we can predict when and where they will likely strike land. Tsunami, or seismic sea waves, generated by disturbance of ocean waters by earthquakes or submarine volcanoes, may also be predicted. The tsunami warning system has been fairly successful in the Pacific Basin and can predict the arrival of the waves. A short time prediction of a hazardous event, such as a hurricane, motivates us to act quickly to reduce potential consequences before the event happens.

Warning. After a hazardous event has been predicted or a forecast has been made, the public must be warned. Information leading to a **warning** about a possible disaster, such as a large earthquake or flood, should move along a path similar to that shown in Figure 5.14. The public does not always welcome such warnings, however, especially when

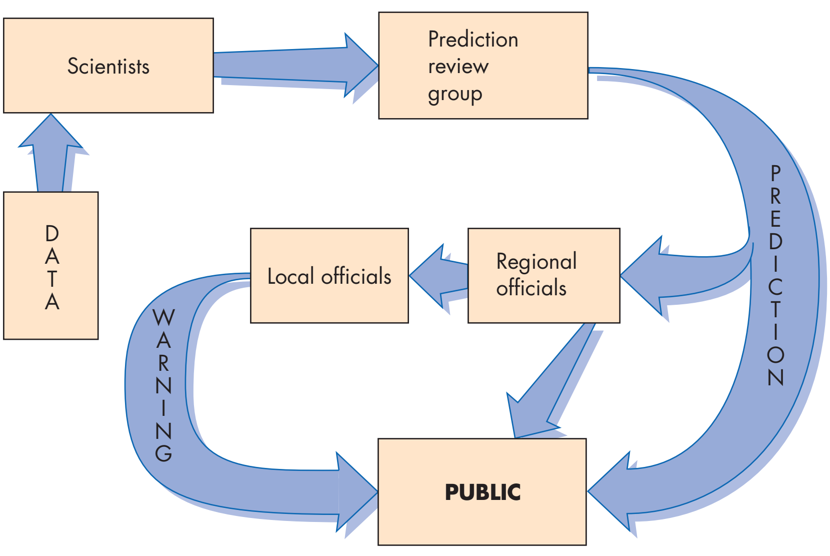


FIGURE 5.14 Hazard prediction or warning Possible flow path for issuance of a natural disaster prediction or warning.

the predicted event does not come to pass. In 1982, when geologists advised that a volcanic eruption near Mammoth Lakes, California, was quite likely, the advisory caused a loss of tourist business and apprehension on the part of the residents. The eruption did not occur, and the advisory was eventually lifted. In July 1986, a series of earthquakes occurred over a 4 day period in the vicinity of Bishop, California, in the eastern Sierra Nevada. The initial earthquake was relatively small and was felt only locally; but a later, larger earthquake causing some damage also occurred. Investigators concluded that there was a high probability that an even larger quake would occur in the same area in the near future and issued a warning. Local business owners, who feared the loss of summer tourism, felt that the warning was irresponsible; in fact, the predicted quake never materialized.

Incidents of this kind have led some people to conclude that scientific predictions are worthless and that advisory warnings should not be issued. Part of the problem is poor communication between the investigating scientists and reporters for the media (see A Closer Look: Scientists, Hazards, and the Media). Newspaper, television, and radio reports may fail to explain the evidence or the probabilistic nature of disaster prediction. This failure leads the public to expect completely accurate statements about what will happen. Although scientific predictions of volcanic eruptions and earthquakes are not always accurate, scientists have a responsibility to publicize their informed judgments. An informed public is better able to act responsibly than an uninformed public, even if the subject makes people uncomfortable. Ship captains, who depend on weather advisories and warnings of changing conditions, do not suggest that they would be better off not knowing about an impending storm, even though the storm might veer and miss the ship. Just as weather warnings have proved very useful for planning ships' routes, official warnings of hazards, such as earthquakes, landslides, and floods, are also useful to people making decisions about where they live, work, and travel.

Consider once more the prediction of a volcanic eruption in the Mammoth Lakes area of California. The seismic data suggested to scientists that molten rock was moving toward the surface. In view of the high probability that the volcano would erupt and the possible loss of life if it did, it would have been irresponsible for scientists not to issue an advisory. Although the eruption did not occur, the warning led to the development of evacuation routes and consideration of disaster preparedness. This planning may prove useful in the future; it is likely that a volcanic eruption will occur in the Mammoth Lakes area in the future. The most recent event occurred only 600 years ago! In the end, the result of the prediction is a better-informed community that will be better able to deal with an eruption when it does occur.

Risk Assessment

Before discussing and considering adjustments to hazards, people must have a good idea of the risk they face under various scenarios. Risk assessment is a rapidly growing field in the analysis of hazards, and its use should probably be expanded.

Risk Determination. The **risk** of a particular event is defined as the probability of that event's occurring multiplied by the consequences should it actually occur.[8] Consequences, such as damages to people, property, economic activity, and public service, may be expressed in a variety of scales. If, for example, we are considering the risk from earthquake damage to a nuclear reactor, we may evaluate the consequences in terms of radiation released, which can further be translated into damage to people and other living things. In any such assessment, it is important to calculate the risks of various possible events—in this example, earthquakes of various magnitudes. A large earthquake has a lower probability of occurring than does a small one, but its consequences are likely to be greater.

Acceptable Risk. Determining *acceptable risk* is complicated. The risk that an individual is willing to endure is dependent upon the situation. Driving an automobile is fairly risky, but most of us accept that risk as part of living in the modern world. However, acceptable risk from a nuclear power plant is very low because we consider almost any risk of radiation poisoning unacceptable. Nuclear power plants are controversial because many people perceive them as high-risk facilities. Even though the probability of a nuclear accident due to a geologic hazard, such as an earthquake, may be quite low, the associated consequences could be high, resulting in a relatively high risk.

A Closer Look: Scientists, Hazards, and the Media

People today learn what is happening in the world by watching television, listening to the radio, surfing the Internet, and reading newspapers and magazines. Reporters for the media are generally more interested in the impact of a particular event on people than in its scientific aspects. Even major volcanic eruptions or earthquakes in unpopulated areas may receive little media attention, whereas moderate or even small events in populated areas are reported in great detail. The news media want to sell stories, and spectacular events that affect people and property "sell."[7]

Establishing good relationships between scientists and the news media is a goal that may be difficult to always achieve. In general, scientists tend to be conservative, critical people who are afraid of being misquoted. They may perceive reporters as pushy and aggressive or as willing to present half-truths while emphasizing differences in scientific opinion to embellish a story. Reporters, on the other hand, may perceive scientists as an uncooperative and aloof group who speak in impenetrable jargon and are unappreciative of the deadlines that reporters face.[7] These statements about scientists and media reporters are obviously stereotypical. In fact, both groups have high ethical and professional standards; nevertheless, communication problems and conflicts of interest often occur, affecting the objectivity of both groups.

Because scientists have an obligation to provide the public with information about natural hazards, it is good policy for a research team to pick one spokesperson to interact with the media to ensure that information is presented as consistently as possible. Suppose, for example, that scientists are studying a swarm of earthquakes near Los Angeles, and speculation exists among them regarding the significance of the swarm. Standard operating procedure for Earth scientists working on a problem is to develop several working hypotheses and future scenarios. However, when scientists are working with the news media on a topic that concerns people's lives and property, their reports should be conservative evaluations of the evidence at hand, presented with as little jargon as possible. Reporters, for their part, should strive to provide their readers, viewers, or listeners with accurate information that the scientists have verified. Embarrassing scientists by misquoting them will only lead to mistrust and poor communication between scientists and journalists.

Institutions such as the government and banks approach the topic of acceptable risk from an economic point of view rather than a personal perception of the risk. For example, a bank will consider how much risk it can tolerate with respect to flooding. The federal government may require that any property that receives a loan from that bank not have a flood hazard that exceeds 1 percent per year—that is, protection up to and including a 100 year flood.

Problems and Opportunities for Risk Assessment. A frequent problem of risk analysis, with the exception of flooding on a river with a long record of past floods, is lack of reliable data available for analyzing the probability of an event. It can be difficult to assign probabilities to geologic events, such as earthquakes and volcanic eruptions, because the known chronology of past events is often inadequate.[8] Similarly, it may be difficult to determine the consequences of an event or a series of events. For example, if we are concerned about the consequences of releasing radiation into the environment, local biological, geologic, hydrologic, and meteorological information must be gathered to evaluate the radiation's effects. This information may be complex and difficult to analyze. Despite these limitations, methods of determining the probability of earthquakes and volcanic eruptions are improving, as is our ability to estimate consequences of hazardous events. Certainly, risk assessment is a step in the right direction and should be expanded. As more is learned about determining the probability and

consequences of a hazardous event, we will be able to provide more reliable forecasts and predictions necessary for decision making, such as when to issue a warning or evacuate people from harm's way.

5.3 The Human Response to Hazards

Often, the manner in which we deal with hazards is primarily *reactive*. After a disaster, we engage in searching for and rescuing survivors, firefighting, and providing emergency food, water, and shelter. There is no denying that these activities reduce loss of life and property and need to be continued. However, the move to a higher level of hazard reduction will require increased efforts to *anticipate* disasters and their impact. Land use planning to avoid hazardous locations, hazard-resistant construction, and hazard modification or control, such as flood control channels, are some of the adjustments that anticipate future disastrous events and may reduce our vulnerability to them.[6]

Reactive Response: Impact of and Recovery from Disasters

The impact of a disaster upon a population may be either direct or indirect. *Direct effects* include people killed, injured, displaced, or otherwise damaged by a particular event. *Indirect effects* generally include responses to the disaster, such as emotional distress, donation of money or goods, and payment of taxes to finance the recovery. Direct effects are felt only by those individuals immediately affected by the disaster, whereas indirect effects are felt by the populace in general.[9,10]

The stages of recovery following a disaster are emergency work, restoration of services and communication lines, and reconstruction. **Figure 5.15** shows

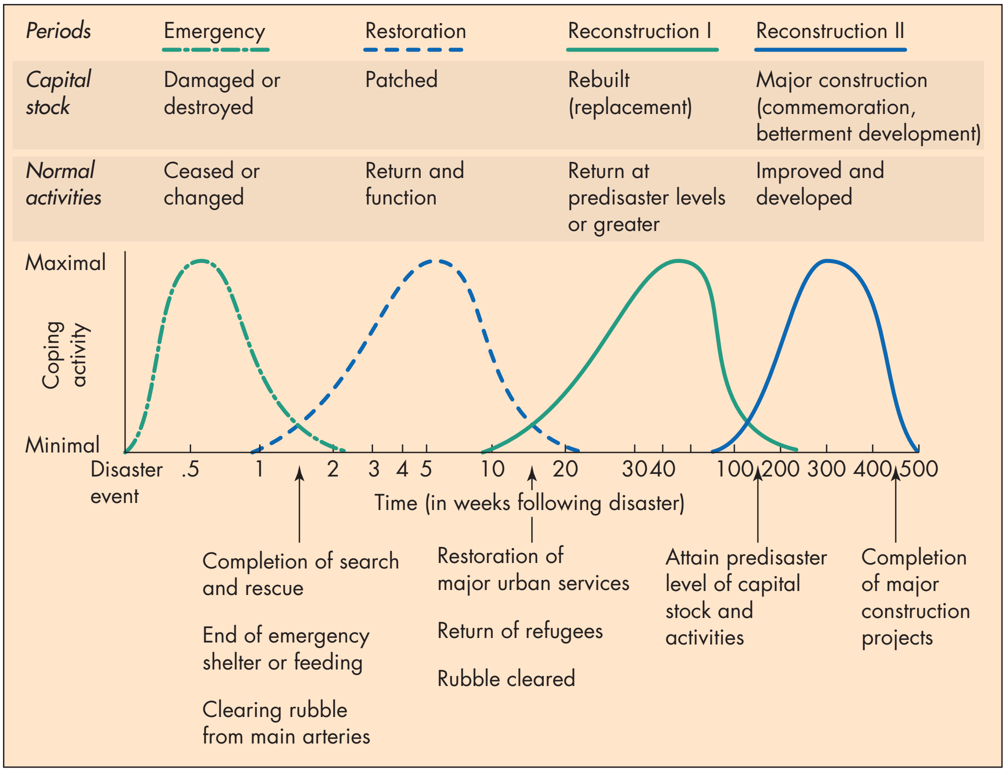


FIGURE 5.15 Recovery from disaster Generalized model of recovery following a disaster. The first 2 weeks after a disaster are spent in a state of emergency, in which normal activities are ceased or changed. During the following 19 weeks, in the restoration phase, normal activities return and function, although perhaps not at predisaster level. During the reconstruction I phase, for almost 4 years after a disaster, the area is being rebuilt, and normal activities return to predisaster levels. Finally, during reconstruction II, major construction and development are being done, and normal activities are improved and developed. *(From Kates, R. W., and Pijawka, D. 1977. Reconstruction following disaster. In* From Rubble to Monument: The Pace of Reconstruction, *ed. J. E. Haas, R. W. Kates, and M. J. Bowden. Cambridge, MA: MIT Press)*

an idealized model of recovery. This model can be applied to actual recovery activities following events, such as the 1994 Northridge earthquake in the Los Angeles area. Restoration began almost immediately after the earthquake. For example, in the first few weeks and months after the earthquake, roads were repaired and utilities were restored with the help of an influx of dollars from federal programs, insurance companies, and other sources. The damaged areas in Northridge moved quickly from the restoration phase to the reconstruction I stage. We are now well into the reconstruction II period following the Northridge earthquake, and it is important to remember lessons from two previous disasters: the 1964 earthquake that struck Anchorage, Alaska, and the flash flood that devastated Rapid City, South Dakota, in 1972. Anchorage began restoration approximately 1 month after the earthquake, as money from federal programs, insurance companies, and other sources poured in. As a result, reconstruction was a hectic process, with different groups and individuals trying to obtain as much of the available funds as possible. In Rapid City, on the other hand, the restoration did not peak until approximately 10 weeks after the flood. The community took time to carefully think through the best alternatives to avoid future flooding problems. As a result, Rapid City today has an entirely different land use on the floodplain. The floodplain is now a greenbelt, with golf courses and other such activities, which has greatly reduced the flood hazard in the area (**Figure 5.16**). Conversely, the rapid restoration and reconstruction in Anchorage were accompanied by little land-use planning. Apartments and other buildings were hurriedly constructed across areas that had suffered ground rupture and had simply been filled in and regraded. By ignoring the potential benefits of careful land-use planning, Anchorage is vulnerable to the same type of earthquake damage that it suffered in 1964.[6,9,10]

In Northridge, the effects of the earthquake on highway overpasses and bridges, buildings, and other structures have been carefully evaluated to determine how improved engineering standards for construction of new structures or strengthening of older structures might be implemented during the reconstruction II period (Figure 5.15). Future earthquakes of moderate to large intensity are certain to occur again in the Los Angeles area. Therefore, we must continue efforts in the area of earthquake hazard reduction.

FIGURE 5.16 Floodplain management In Rapid City, South Dakota, a 1972 flood, prior to management, killed over 200 people and destroyed many homes in the floodplain. The floodplain of Rapid Creek downstream of Canyon Lake (center) is now the site of a golf course (lower left). *(Courtesy of Perry Rahn)*

Anticipatory Response: Perceiving, Avoiding, and Adjusting to Hazards

The options we choose, individually or as a society, for avoiding or minimizing the impacts of disasters depend, in part, on our hazard perception. A good deal of work has been done in recent years to try to understand how people perceive various natural hazards. This work is important because the success of hazard-reduction programs depends on the attitudes of the people likely to be affected by the hazard. Although there is informed perception and understanding of a hazard at the institutional level among government agencies, such as the U.S. Geological Survey and state or local flood control agencies, this may not filter down to the general population. This lack of understanding is particularly true with events that occur infrequently; people are more aware of situations, such as large floods and brush or forest fires, that may occur every few years or decades (**Figure 5.17**). There are often local ordinances to help avoid or minimize damages resulting from these events. For example, in some areas of southern California, local regulations stipulate that homes must be roofed with shingles that do not burn readily. Other regulations include mandatory installation of sprinkler systems and require that lots be cleared of brush. Such safety measures are often noticeable during the rebuilding phase following a fire.

One of the most environmentally sound adjustments to hazards involves **land-use planning**. For example, people can avoid building on floodplains, in areas where there are active landslides, or in places where coastal erosion is likely to occur. In many cities, floodplains have been delineated and zoned for a particular land use. With respect to landslides, legal requirements for soil engineering and engineering geology studies at building sites may greatly reduce potential damages. Damages from coastal erosion can be minimized by requiring adequate setback of buildings from the shore line or sea cliff. Although it may be possible to control physical processes in specific instances, land-use planning to accommodate natural processes is often preferable to technology-based solutions that may or may not work.

Insurance. Insurance is another option that people may exercise in dealing with natural hazards. Flood insurance and earthquake insurance are common in many areas. However, because of large losses

FIGURE 5.17 Killer wildfire Wildfire in October 1991 devastated this Oakland, California, neighborhood. This fire killed 25 people and destroyed more than 3,000 homes, with damages of about $1.7 billion. *(Karl Mondon/Contra Costa Times/Newscom)*

following the 1994 Northridge earthquake, several insurance companies announced that they would no longer offer earthquake insurance to residents of the area. Florida homeowners have difficulty obtaining insurance after costly hurricanes in the past decade. Some large private insurance companies have dropped coverage to hundreds of thousands of home owners. Hurricanes typically cause a few billions of dollars in damage, and a direct hit to Miami could inflict damages as high as $50 billion. As a result, Florida has a state sponsored insurance program that may cause a tremendous financial liability to the people of the state should a high magnitude hurricane strike a populated part of the state.

Evacuation. In the states along the Gulf of Mexico and along the eastern coast of the United States, evacuation is an important option or adjustment to the hurricane hazard. Often, there is sufficient time for people to evacuate, provided that they heed the predictions and warnings. However, if people do not react quickly and if the affected area is a large urban region, evacuation routes may be blocked by residents leaving in a last-minute panic. Successful evacuation from areas of volcanic eruptions is mentioned in Chapter 8.

Disaster Preparedness. Individuals, families, cities, states, and even entire nations can practice **disaster preparedness**. Training individuals and institutions to handle large numbers of injured people or people attempting to evacuate an area after a warning is issued is particularly important in disaster preparedness.

Artificial Control of Natural Processes

Attempts at *artificial control of natural processes* such as landslides, floods, and lava flows have had mixed success. Seawalls constructed to control coastal erosion may protect property to some extent but tend to narrow or even eliminate the beach. Even the best-designed artificial structures cannot be expected to adequately defend against an extreme event, although retaining walls and other structures that defend slopes from landslides have generally been successful when well designed (**Figure 5.18**). Even the casual observer has probably noticed the variety of such structures along highways and urban land in hilly areas. These have limited impact on the environment but are necessary where construction demands that artificial cuts be excavated or where unstable slopes impinge on human structures. Common methods of flood control are channelization and construction of dams and levees. Unfortunately, flood control projects tend to provide floodplain residents with a false sense of security; no method can be expected to absolutely protect people and their property from high-magnitude floods. We will return to this discussion in Chapter 9.

All too often, people choose to simply bear the loss caused by a natural disaster. Many people are optimistic about their chances of making it through any sort of disaster and take little action in their own defense, particularly in the cases of hazards such as volcanic eruptions and earthquakes that occur only rarely in a particular area. Regardless of

FIGURE 5.18 Protecting a slope Retaining wall being constructed along a canyon side in an area where landslides were formerly common. The wall protects the homes that were constructed too close to the edge of the steep canyon. If the homes had been built with adequate setback from the canyon, the wall would not be necessary. *(Edward A. Keller)*

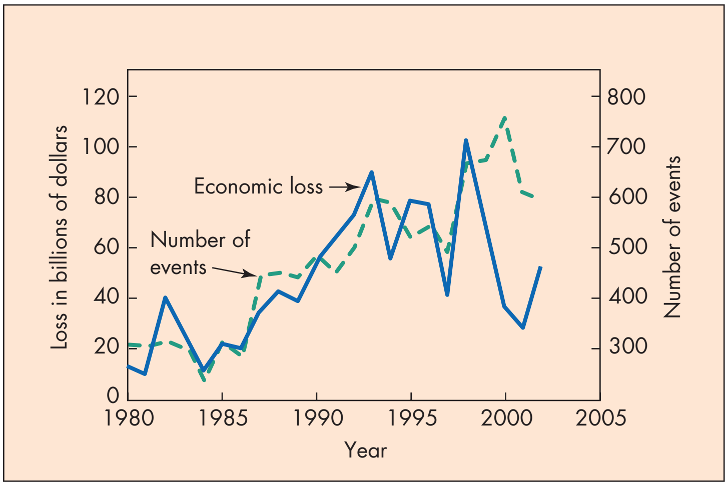


FIGURE 5.19 Severe weather hazards increasing Worldwide number of events and economic losses from weather-related natural hazards (1980–2002). *(Modified after Sawing, J. L. 2003.* Vital Signs. *New York: W. W. Norton. World Watch Institute)*

the strategy we choose either to minimize or to avoid hazards, it is imperative that we understand and anticipate hazards and their physical, biological, economic, and social impacts.

5.4 Global Climate and Hazards

Global and regional climatic change may significantly affect the incidence of hazardous natural events, such as storms (i.e., floods, erosion), landslides, drought, and fires. Global warming associated with climate change may also have an impact on natural hazards. (We will discuss global warming in detail in Chapter 18.)

How might a climatic change affect the magnitude and frequency of disastrous natural events? As a result of global warming, sea level will rise as glacial ice melts and warming ocean waters expand. This rise in sea level will lead to an increase in coastal erosion. With a change in climatic patterns, food production areas will shift as some regions receive more precipitation and others less than they do now. Deserts and semiarid areas would likely expand, and more northern latitudes could become more productive. Such changes could lead to global population shifts, which could precipitate wars or major social and political upheavals.

Global warming, with warming of the oceans of the world, will channel more energy from warmer ocean water into the atmosphere. Warming the atmosphere will likely increase the frequency and severity of hazardous weather-related processes, including thunderstorms, tornadoes, and hurricanes (Figure 5.19). Worldwide, the impact on people from weather-related disasters in the past two decades was catastrophic, killing several tens of thousands of people and displacing several hundred million people from their homes while inflicting over $100 billion in damages.[11] The trend is clear: The number of severe weather events (e.g., storms, floods, drought, heat waves, cold) are increasing.

5.5 Population Increase, Land Use Change, and Natural Hazards

Population Increase and Hazardous Events

Population growth throughout the world is a major environmental problem. And, as our population increases, the need for planning to minimize losses from natural disasters also increases. Specifically, an increase in population puts a greater number of people at risk from a natural event; it also forces more people to settle in hazardous areas, creating additional risks. The risks of both high population density and living in a danger zone are dramatically illustrated by the loss of thousands of lives in Colombia in 1985. (See A Closer Look: Nevado del Ruiz: A Story of People, Land Use, and Volcanic Eruption.)

Mexico City provides another example of the risks associated with high population density coupled with living in a dangerous zone. Mexico City is the center of the world's most populous urban area. Approximately 23 million people are concentrated in an area of about 2,300 km^2 (890 mi^2), and about one-third of the families live in a single room. The city is built on ancient lake beds that accentuate earthquake shaking, and parts of the city have been sinking at the rate of a few centimeters per year, due in part to groundwater withdrawal. The subsidence has not been uniform, so the buildings tilt and are even more vulnerable to the shaking of earthquakes.[12] In September 1985, Mexico endured a

large damaging earthquake that killed about 10,000 people in Mexico City alone. Haiti, with rapid human population growth, experienced a catastrophic earthquake in 2010 that damaged or destroyed about 200,000 homes and buildings. About one third of the population of Haiti were directly affected by the earthquake, and more than 250,000 people were killed (see Chapter 1 opening case history). With fewer people crammed into the capital city, and fewer people living in substandard buildings that could not withstand earthquake shaking there would have been far fewer deaths in Haiti.

Land Use Change and Hazardous Events

During the past 20 years a large number of great catastrophes occurred worldwide. Although there are several hundred disasters from natural hazardous events each year, only a few are classified as great catastrophes that result in deaths or losses so great that outside assistance is required.[13] During the past half-century, there has been a dramatic increase in great catastrophes, as illustrated in **Figure 5.20**. For these events, flooding is the major killer of people, followed by earthquakes, volcanic eruptions, and windstorms. The vast majority of deaths (over 95 percent in recent years) has been in developing countries. Asia has suffered the greatest losses with the majority of total deaths and economic losses. Losses on a global scale (all countries included) would be even worse if it were not for improvements in warning, disaster preparedness, and sanitation following disasters.[3,13] Nevertheless, economic losses have increased at a faster rate than have the number of deaths.

Four of the deadly catastrophes resulting from natural hazards linked to changes in land use were Hurricane Mitch in 1998, which devastated Central America; the 1998 flooding of the Yangtze River in China; Hurricane Katrina in 2005; and the 2010 flooding of the Indus River in Pakistan. Hurricane Mitch caused approximately 11,000 deaths, and the floods in the Yangtze River resulted in nearly 4,000 deaths. It has been speculated that damages from these events in Central America and China were particularly severe because of land use changes that had occurred. For example, Honduras has already lost nearly half of its forests due to timber harvesting, and a fire in an area of about 11,000 km^2 (4,250 mi^2) occurred in the region before the hurricane. As a result of the previous deforestation and the fire,

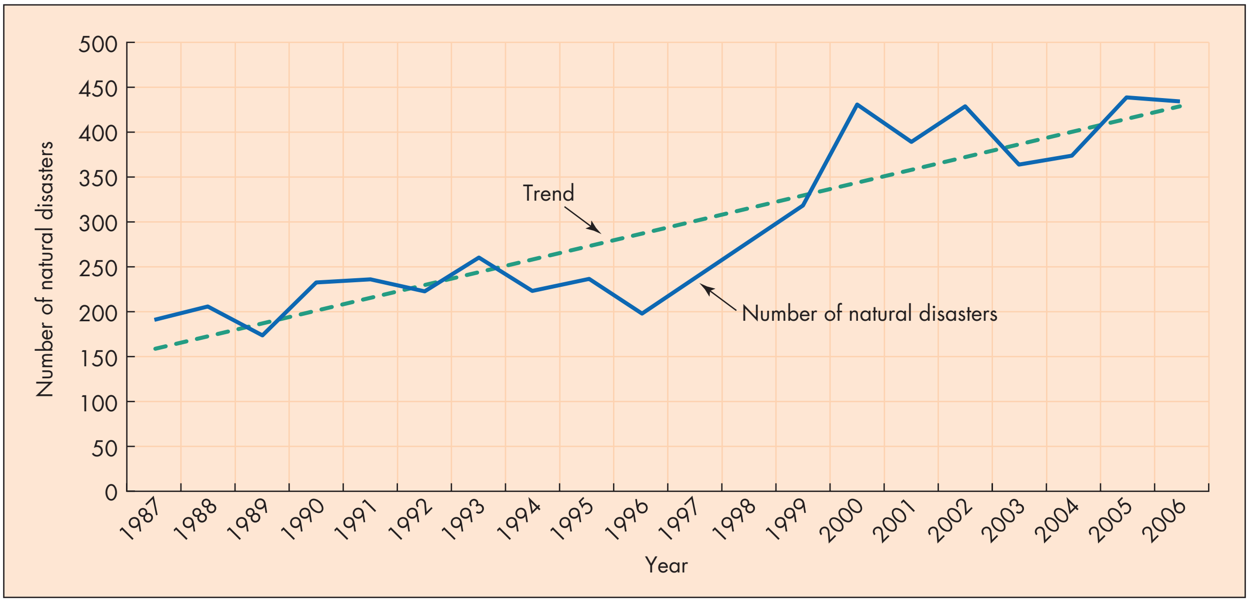


FIGURE 5.20 The number of natural disasters in the world is increasing The operating definition or criteria for a disaster are 10 or more people killed, 100 or more people affected, state of emergency declared, and international assistance requested. If any one of these applies, an event is considered a natural disaster by the Center for Research on the Epidemiology of Disasters (CRED). *(Modified by CRED 2007. Hoyois, P., Below, R., Scheuren, J-M., and Guha-Sapir, D.* Annual Disaster Statistical Review: Numbers and Trends, 2006. *University of Louvain, Brussels, Belgium.)*

A Closer Look

Nevado del Ruiz: A Story of People, Land Use, and Volcanic Eruption

A fundamental principle of this chapter is that population increase, coupled with poor land use choices as well as land use changes (for example, forested land with steep slopes transformed for urban uses), has intensified impacts of natural hazards. In some cases, disasters from natural hazards have become catastrophes. For example, when the Colombian volcano Nevado del Ruiz erupted in 1845, a mudflow roared down the eastern slope of the mountain, killing approximately 1,000 people. Deposits from that event produced rich soils in the Lagunillas River valley, and an agricultural center developed there. The town that the area supported was known as Armero, and by 1985 it was a prosperous community with a growing population of about 23,000 people. On November 13, 1985, another mudflow associated with a volcanic eruption buried Armero, leaving about 21,000 people dead or missing and inflicting more than $200 million in property damage. It was population increase during the 140 years between the mudflows that multiplied the death toll by more than 20 times. The flat lands and rich soil produced by the previous volcanic eruption lured people into a hazardous area. Ironically, the area was decimated by the same type of event that had earlier produced productive soils, stimulating development and population growth.[14]

The volcanic eruption of November 13, 1985, followed a year of precursor activity, including earthquakes and hot-spring activity. Volcano monitoring began in July 1985, and in October a hazards map was completed that correctly identified the events that occurred on November 13. The report and accompanying map gave a 100 percent probability that potentially damaging mudflows would be produced by an eruption, as had been the case with previous eruptions.

The November 13 event, as expected, started with an explosive eruption that produced pyroclastic flows of hot volcanic ash that scoured and melted glacial ice on the mountain. The ash and melting glacial ice produced water that generated mudflows that raced down river valleys. **Figure 5.C** shows the areas affected by magma that came into contact

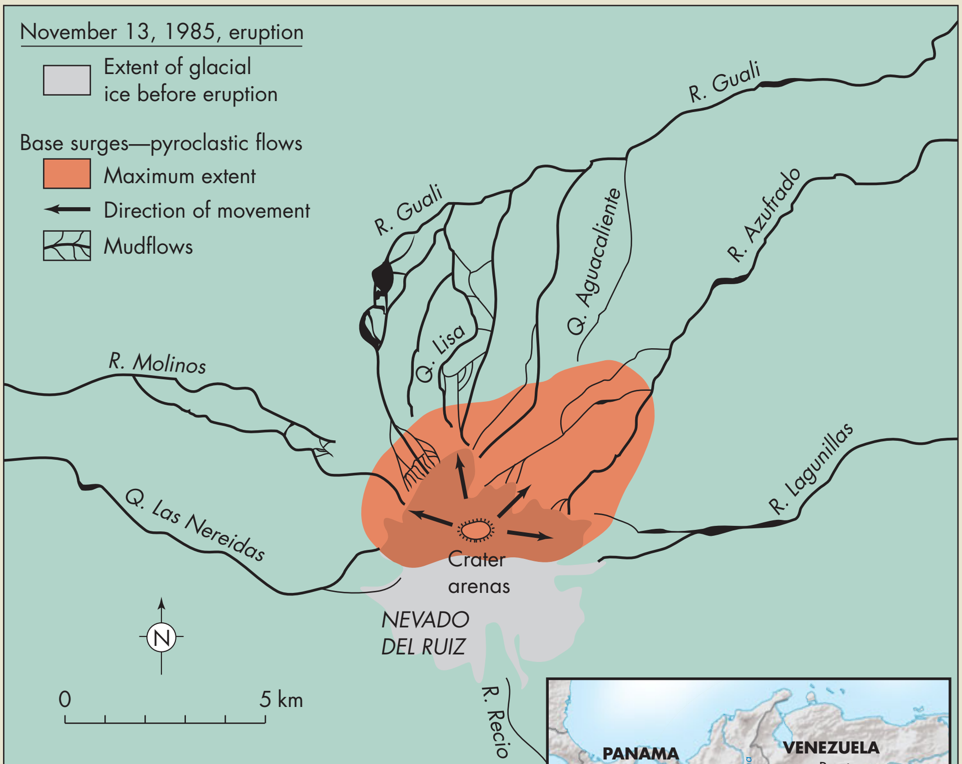


FIGURE 5.C Eruption of Nevado del Ruiz Map of the volcano Nevado del Ruiz area, showing some of the features associated with the eruption of November 13, 1985. *(Modified after Herd, D. G. 1986. The Ruiz volcano disaster. EOS, Transactions of the American Geophysical Union, May 13:457–460)*

(a) (b)

FIGURE 5.D Nevado del Ruiz (a) The volcano before the eruption. *(Bettmann/Corbis)* (b) Catastrophic mudflow: The eruption generated a mudflow that nearly destroyed the town of Armero, killing 21,000 people. *(J. Langevin/Corbis)*

with water or ice, causing violent steam and ash explosions, called *base surges*, and pyroclastic flows. It also shows the location of glacial ice that contributed the water necessary to produce the mudflows. Of particular significance was the mudflow that raced down the River Lagunillas and destroyed part of the town of Armero, where most of the deaths occurred. Figure 5.D shows the volcano and the town of Armero. Mudflows buried the southern half of the town, sweeping buildings completely off their foundations.[15]

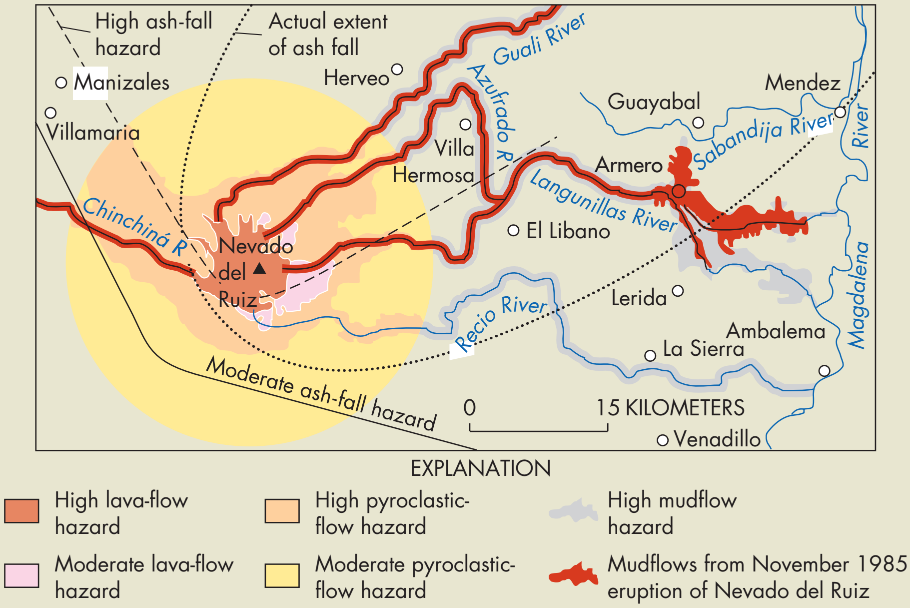


FIGURE 5.E Volcanic hazard map Produced and circulated 1 month before the November 13, 1985, eruption of Nevado del Ruiz and mudflows that buried Armero, Colombia. The actual mudflow deposits are shown in red. *(Wright, T. L., and Pierson, T. C. 1992. U.S. Geological Survey Circular 1973)*

The real tragedy of the catastrophe was that the outcome was predicted; in fact, there were several attempts to warn the town and evacuate it. Hazard maps were circulated in October, but they were largely ignored. Figure 5.E shows the hazard map of events expected before the eruption and the events that occurred. This graphically illustrates the usefulness of volcanic risk maps.[16] Despite these warnings, there was little response, and, as a result, approximately 21,000 people died. Early in 1986, a permanent volcano observatory center was established in Colombia to continue monitoring the Ruiz volcano, as well as others in South America. South America should now be better prepared to deal with volcanic eruptions. Had there been better communication lines from civil defense headquarters to local towns and a better appreciation of potential volcanic hazards even 40 km (about 25 mi) from the volcano, evacuation would have been possible for Armero. It is hoped that the lessons learned from this event will help minimize future loss of life associated with volcanic eruptions and other natural disasters.

FIGURE 5.21 Hurricane disaster Homes destroyed by flooding and landslides in Honduras from Hurricane Mitch in 1998. *(Luis Elvir/AP Photo)*

hillsides were stripped of vegetation and washed away; along with them went farms, homes, roads, and bridges (**Figure 5.21**). The story is similar in central China; recently, the Yangtze River basin lost about 85 percent of its forest as a result of timber harvesting and conversion of land to agriculture. As a result of the land use changes in China, flooding of the Yangtze River is probably much more common than it was previously.[11] Hurricane Katrina (see the case history at the beginning of this chapter) emphasized several poor land use choices, including the removal of coastal wetlands that provide a buffer to wind and storm waves. The population of Pakistan has increased by more than 130 million people in the past 60 years, and many more people are living along the river with a high flood risk. The 2010 floods killed over 1,500 people while displacing about 20 million people.

The hazardous events that caused catastrophes since the late 1990s in Central America, the Caribbean, Asia, China, the United States, and other parts of the world may be early warning signs of things to come. It is apparent that human activities are likely increasing the impacts of natural disasters. In recognition of the influence of human activities, China has banned timber harvesting in the upper Yangtze River basin, has prohibited imprudent floodplain land uses, and has allocated several billion dollars for reforestation. The lesson being learned is that, if we wish to minimize damages from natural hazards in the future, we need to consider human population growth and land rehabilitation. The goal must be to achieve sustainable development based on both restoration and maintenance of healthy ecosystems.[11] This goal will be difficult to reach, given the pressures of human population growth in many parts of the world. The effects of population increase emphasize the need to control human population growth if we are to solve pressing environmental problems and reach our goal of sustaining our environment.

Making The Connection

Linking the Opening Case History About Hurricane Katrina to the Fundamental Concepts

Consider and discuss the following questions:

1. Was damage to New Orleans from Katrina completely the result of a natural disaster, or did actions of people have significant roles?
2. How are human population, sustainability, and understanding the Gulf of Mexico as a system linked to the future of New Orleans? What is the role of our values?

Summary

Our discussion of natural processes suggests a view of nature as dynamic and changing. This understanding tells us that we cannot view our environment as fixed in time. A landscape without natural hazards would also have less variety; it would be safer but less interesting and probably less aesthetically pleasing. The jury is still out on how much we should try to control natural hazards and how much we should allow them to occur. However, we should remember that disturbance is natural and that management of natural resources must include management for and with disturbances such as fires, storms, and floods.

A fundamental principle of environmental geology is that there have always been Earth processes that are dangerous to people. These become hazards when people live close to the source of danger or when they modify a natural process or landscape in a way that makes it more dangerous. Natural events that will continue to cause deaths and property damage include flooding, landslides, earthquakes, volcanic activity, wind, expansive soils, drought, fire, and coastal erosion. The frequency of a hazardous event is generally inversely related to its magnitude; its impact on people depends on its frequency and magnitude, as well as on such diverse factors as climate, geology, vegetation, and human use of the land. The same natural events that create disasters may also bring about benefits, as when river flooding or a volcanic eruption supplies nutrients to soils.

The events causing the greatest number of deaths in the United States are tornadoes and windstorms, lightning, floods, and hurricanes, although a single great earthquake can take a very large toll. Floods, landslides, frost, and expansive soils cause the greatest property damage. Events most likely to produce a catastrophe are floods, hurricanes, tornadoes, earthquakes, volcanic eruptions, and fires. Although in the United States land use changes, urbanization, and population increase are causing damages from most hazards to increase, better predictions and warning systems are reducing the number of deaths from these hazardous processes.

Some disastrous events can be forecast or predicted fairly accurately, including some river floods and the arrival of coastal hurricanes and tsunamis. Precursor events can warn experts about impending earthquakes and volcanic eruptions. Once an event has been forecast or predicted, this information must be made available to planners and decision makers in order to minimize the threat to human life and property. The manner in which a warning is issued and how scientists communicate with the media and public are particularly significant. For many hazards, we cannot determine when a specific event will occur but only note the probability of occurrence, based on the record of past occurrences. The risk associated with an event is the product of the event's probability of occurrence and the likely consequences, should it actually occur.

The impact of a disaster upon a population includes direct effects, such as people killed, dislocated, or otherwise damaged, and indirect effects, such as emotional distress, donation of money or goods, and payment of taxes to finance recovery. Recovery often has several stages, including emergency work, restoration of services and communication, and reconstruction.

The options that individuals or societies choose for avoiding or adjusting to natural hazards depend in part on how hazards are perceived. People tend to be more aware of hazards that are likely to occur often, such as the several hurricanes in the Atlantic that could strike the East and Gulf Coasts of North America each year. Options to adjust to hazards range from land use planning, insurance, and evacuation to disaster preparedness and artificial control of natural processes. For hazards that occur rarely in particular areas, people often choose to just bear the loss incurred from the hazard. Attempts to artificially control natural processes have had mixed success and usually cannot be expected to defend against extreme events. Regardless of the approach we choose, we must increase our understanding of hazards and do a better job of anticipating them.

As the world's population increases and we continue to modify our environment through changes such as urbanization and deforestation, more people will live on marginal lands and in hazardous locations. As a result of population pressure and land use changes, what were formerly localized hazards and disasters are now becoming catastrophes. Therefore, as population increases, better planning at all levels will be necessary if we are to minimize losses from natural hazards.

Revisiting Fundamental Concepts

Human Population Growth

Increase in human population is forcing many people to live in areas where natural hazards are more likely, such as on floodplains, steep slopes, and flanks of volcanoes. Population pressure has accelerated land use changes as more land is urbanized, farmed, mined, and harvested for timber. As a result, hazardous events that were formerly disasters are becoming catastrophes.

Sustainability Living in hazardous areas such as on floodplains is not a sustainable practice, as communities will continue to suffer property damage and loss of life. Ensuring that future generations inherit a quality environment requires that we minimize losses from natural hazards. We cannot sustain soil resources if we continue to log forests on steep slopes, thereby increasing the occurrence of landslides and flooding that erode soil.

Earth as a System Dynamic Earth systems, such as the atmosphere, hydrosphere, and lithosphere, are responsible for producing processes that are hazardous to people. Change in one part of a system affects other parts, often in a complex way. For example, the burning of fossil fuels is releasing carbon dioxide into the atmosphere, causing global warming. One result is that some places will receive more rain and experience more violent storms. These increases will cause changes in the intensity of floods and landslide activity.

Scientific Knowledge and Values Intensive study of hazardous Earth processes has greatly increased our knowledge of where these processes occur, how they work, the damages they do, and how best to minimize damages. People's values, coupled with scientific knowledge, will determine, in part, the choices we make to reduce the impact of hazardous events. For example, study of hospitals and schools in an earthquake-prone region may reveal that many are old and likely to fail during a large earthquake. Fixing the hospitals and schools to withstand shaking is a logical answer, but it may cost billions of dollars. Our value of human life compared with other values will determine whether we spend the money to do the necessary work to strengthen the hospitals and schools.

Key Terms

catastrophe (p. 149)
disaster preparedness (p. 159)
forecast (p. 152)
land use planning (p. 158)
magnitude–frequency concept (p. 145)
natural disaster (p. 142)
precursor events (p. 153)
prediction (p. 152)
risk (p. 154)
warning (p. 153)

Review Questions

1. What were the two main lessons learned from the 1985 eruption of Nevado del Ruiz in Colombia?
2. What is a catastrophe, and how does it differ from a disaster?
3. What do we mean by the *magnitude* and *frequency* of a natural process?
4. What is the main conclusion of the magnitude–frequency concept?
5. What is the role of history in understanding natural hazards?
6. List some potential linkages between hazardous events.
7. What are some of the methods of predicting where a disaster is likely to occur?
8. What is the difference between a forecast and a prediction?
9. Why do you think there are sometimes strained relationships between the media and scientists?
10. How may the risk of a particular event be defined?
11. What is the difference between a reactive response and an anticipatory response in hazard reduction?
12. What are some of the common adjustments that limit or reduce the effects of natural hazards?
13. What is the role of global climate in the occurrence of natural hazardous events?
14. How does human population increase result in disasters becoming catastrophes?

Critical Thinking Questions

1. List all the natural processes that are hazardous to people and property in the region where you live. What adjustments have you and the community made to lessen the impacts of these hazards? Could more be done? What? Which alternatives are environmentally preferable?
2. Assume that in the future we will be able to predict with a given probability when and where a large damaging earthquake will occur.

If the probability that the earthquake will occur on a given date is quite low, say 10 percent, should the general public be informed of the forecast? Should we wait until a 50 percent confidence or even a 90 percent confidence is assured? Does the length of time between the forecast and the event have any bearing on your answers?

3. Find a friend, and one of you take the role of a scientist and the other a news reporter. Assume that the news reporter is interviewing the scientist about the nature and extent of hazardous processes in your town. After the interview, jot down some of your thoughts concerning ways in which scientists communicate with newspeople. Are there any conflicts?

4. Develop a plan for your community to evaluate the risk of flooding. How would you go about determining an acceptable risk?

5. Do you agree or disagree that land use change and population increase are increasing the risk from natural processes? Develop a hypothesis and discuss how it might be tested.

Companion Website

www.mygeoscienceplace.com

PEARSON mygeoscience place™

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

2009 L'Aqila, Italy, A strong earthquake hit the mid level town of L'Aqila, Italy, in 2009, killing several hundred people with total collapse of many older buildings not constructed to withstand earthquake shaking. *(Christophe Simon/AFP/Getty Images)*

6 Earthquakes

Learning Objectives

The study of earthquakes is an exciting field with significant social consequences, including potential catastrophic loss of life; damage or loss of homes, large buildings, and infrastructure, such as roads, train tracks, airports, dams, and power plants; disruption of people's lives; and loss of income. In this chapter, we focus on the following learning objectives:

- **Understand the relationship of earthquakes to faulting**
- **Understand how the magnitude of an earthquake is determined**
- **Know the types of earthquake waves, their properties, and how strong ground motion is produced**
- **Understand how seismic risk is estimated**
- **Know the major effects of earthquakes**
- **Understand the components of the earthquake cycle**
- **Understand the methods that could potentially predict earthquakes**
- **Understand the processes of earthquake hazard reduction and how people adjust to and perceive the hazard**

Case History

Italian Earthquake of 2009 and Haiti Earthquake of 2010

Catastrophic earthquakes are devastating events that can destroy large cities and take thousands of lives in a matter of seconds. Many millions of people live in hazardous areas with substandard protection against earthquakes. As human population continues to increase in vulnerable areas, the risk will continue to increase.

A strong earthquake (magnitude 6.3) struck the midlevel town of L'Aqila in 2009, and many of the buildings collapsed, killing about 300 people. A similar earthquake in California probably would have caused no or very few deaths. The Italian event was a catastrophe because the buildings were not constructed to sustain moderate seismic shaking.[1] It is a classic case of people not heeding warnings about future earthquakes and continuing to build substandard structures. The Italian earthquake was a human-caused catastrophe that could have and should have been avoided. California and other places that design and construct buildings resistant to collapse during earthquake shaking may suffer damage from an earthquake, but human loss of life is minimized. Until older buildings are retrofitted to withstand seismic shaking and new buildings are held to a higher engineering standard, earthquakes will continue to take many more lives in places that face earthquake hazard.

On January 12, 2010, a major earthquake (magnitude 7.0) struck Haiti and killed about 240,000 people (an appalling loss of life).[2] Earthquakes in recent years that have taken thousands of lives have a common dominator: They usually cause tremendous loss of life because the buildings people were in collapsed. In Haiti, homes, schools, hospitals, and industrial buildings were subject to collapse during strong shaking because they were not constructed with earthquakes in mind or because the required construction codes were ignored—presumably to save money. In short, most deaths were human-caused.[3] We have experience with strong shaking in California (Northridge in 1994) and, more recently, in Chile (February 27, 2010), where a magnitude 8.8 earthquake, about 500 times as strong as the Haiti earthquake a month earlier, killed about 800 people—an astronomically lower number than in Haiti.[4] Where buildings are designed to withstand shaking and are built properly, as are many in Chile and California, deaths from collapsed buildings are many times lower than in areas where construction is substandard.

6.1 Introduction to Earthquakes

There are approximately 1 million earthquakes a year that can be felt by people somewhere on Earth. However, only a small percentage of these can be felt very far from their source. Earthquakes can be compared with one another by the energy they release, known as their *magnitude*, or by their intensity of shaking, referred to as *ground motion*, and the resulting impact on people and society. **Table 6.1** lists selected major earthquakes that have struck the United States since the early nineteenth century.

6.2 Earthquake Magnitude

When a news release is issued about an earthquake, it generally gives information about where the earthquake started, known as the epicenter. The **epicenter** is the location on the surface of Earth above the **focus**, which is the point at depth where the rocks ruptured to produce the earthquake (**Figure 6.1**, page 172). The news also reports **moment magnitude**, which is a measure of the energy released by the earthquake. The moment magnitude is based, in part, upon important physical characteristics, including the seismic moment, the area that ruptured along a fault plane during an earthquake, the amount of movement or

TABLE 6.1 Selected Major Earthquakes in the United States

Year	Location	Damage (millions of dollars)	Number of Deaths
1811–1812	New Madrid, Missouri	Unknown	Unknown
1886	Charleston, South Carolina	23	60
1906	San Francisco, California	524	700
1925	Santa Barbara, California	8	13
1933	Long Beach, California	40	115
1940	Imperial Valley, California	6	9
1952	Kern County, California	60	14
1959	Hebgen Lake, Montana (damage to timber and roads)	11	28
1964	Alaska and U.S. West Coast (includes tsunami damage from earthquake near Anchorage)	500	131
1965	Puget Sound, Washington	13	7
1971	San Fernando, California	553	65
1983	Coalinga, California	31	0
1983	Central Idaho	15	2
1987	Whittier, California	358	8
1989	Loma Prieta (San Francisco), California	5,000	62
1992	Landers, California	271	1
1994	Northridge, California	40,000	57
2001	Seattle, Washington	2,000	1
2002	South-central Alaska	(sparsely populated area)	0

fault slip during an earthquake, and the rigidity (i.e., shear modulus) of the rocks. The seismic moment is estimated by examining the records from seismographs (i.e., instruments that record earthquake motion), determining the amount and length of rupture, and estimating the shear modulus (from laboratory testing of rocks). The moment magnitude (M_w) is then determined by $M_w = 2/3 \log M_0 - 10.7$, where M_0 is the seismic moment.

Before the use of moment magnitude, *Richter magnitude*, named after the famous seismologist Charles Richter, was used to describe the energy released by an earthquake. Richter magnitude is based upon the *amplitude*, or size, of the largest seismic wave produced during an earthquake. A *seismograph* is an instrument that records earthquake displacements; seismographs produce *seismographic records*, or *seismograms*. The amplitude recorded is converted to a magnitude on a logarithmic scale; that is, each integer increase in Richter magnitude represents a tenfold increase in amplitude. For example, a Richter magnitude 7 earthquake produces a displacement on the seismogram 10 times larger than does a magnitude 6. Although the Richter magnitude remains the best-known earthquake scale to many people, earthquake scientists, known as *seismologists*, do not commonly use it. For large, damaging earthquakes, the Richter magnitude is approximately equal to the moment magnitude, which is more commonly used today. In this book, we will simply refer to the size of an earthquake as its magnitude, M, without designating a Richter or moment magnitude.

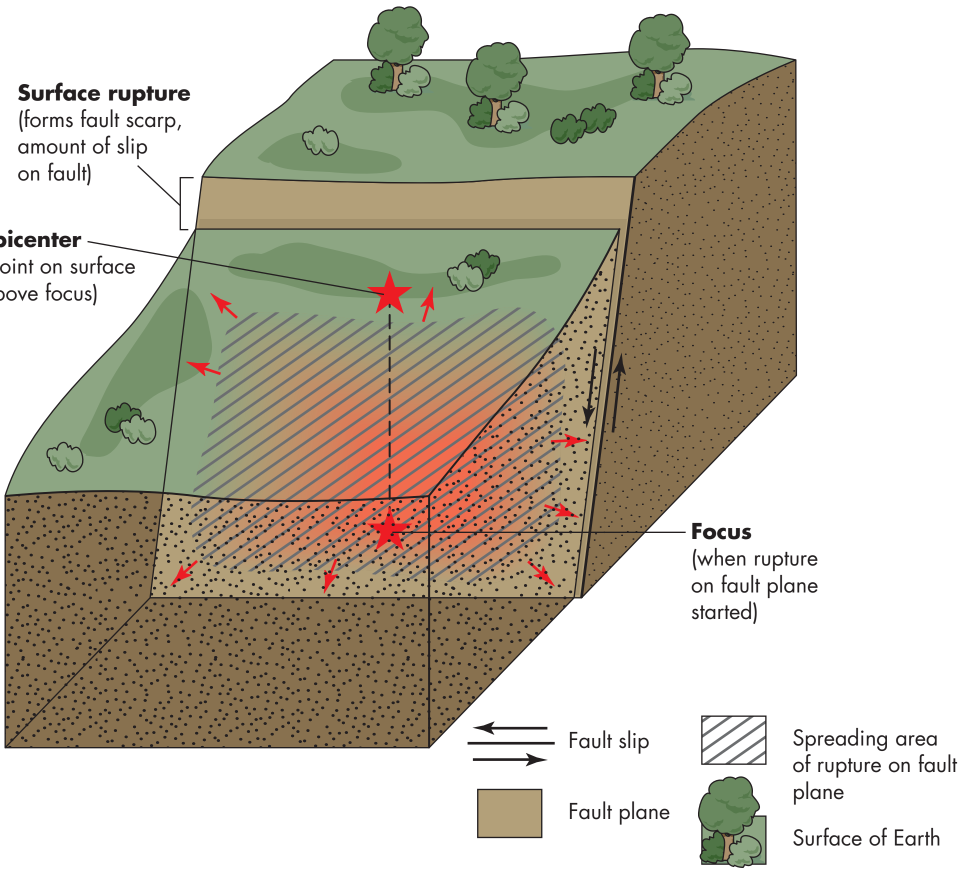


FIGURE 6.1 Basic earthquake features Block diagram showing fault plane, amount of displacement, rupture area, focus, and epicenter. Rupture starts at the focus and propagates up, down, and laterally. During a major to giant earthquake, slip may be 2 to 20 m along a fault length of 100 km or more. Rupture area may be 1,000 km^2 or more.

The magnitude and frequency of earthquakes worldwide are shown in Table 6.2. An event of magnitude 8 (M 8) or above is considered a *great earthquake*, capable of causing widespread catastrophic damage. In any given year, there is a good chance that one M 8 event will occur somewhere in the world. A M 7 event is a *major earthquake*, capable of causing widespread and serious damage. Magnitude 6 signifies a *strong earthquake* that can cause considerable damage, depending upon factors such as location, surface materials, and quality of construction. Ground motion can be recorded as the displacement or actual separation of rocks produced by an earthquake. Relationships between change in magnitude and change in displacement and energy are shown in Table 6.3. This table illustrates that the difference between a M 6 and a M 7 earthquake is considerable. A M 7 earthquake releases about 32 times more energy than a M 6 earthquake, and the amount of displacement, or ground motion, is 10 times greater. If we compare a M 5 with a M 7 earthquake, the differences are much greater. The energy released is about 1,000 times greater. The topic of earthquake magnitude is introduced here to help compare the severity of earthquakes. We will return to a more detailed discussion of this topic later in this chapter when earthquake processes are discussed.

Earthquake Catastrophes

Catastrophic, or great, earthquakes are devastating events that can destroy large cities and take thousands of lives in a matter of seconds. A sixteenth-century earthquake in China reportedly claimed 850,000 lives. More recently, a 1923 earthquake near Tokyo killed 143,000 people, and a 1976 earthquake in China killed

TABLE 6.2 Worldwide Magnitude and Frequency of Earthquakes, by Descriptor Classification

Descriptor	Magnitude	Average Annual Number of Events
Great	8 and higher	1
Major	7–7.9	18
Strong	6–6.9	120
Moderate	5–5.9	800
Light	4–4.9	6,200 (estimated)
Minor	3–3.9	49,000 (estimated)
Very minor	<3.0	Magnitude 2–3, about 1,000 per day
		Magnitude 1–2, about 8,000 per day

U.S. Geological Survey. 2000. *Earthquakes, Facts and Statistics.* http://neic.usgs.gov. Accessed 1/3/00.

TABLE 6.3 Relationships Between Magnitude, Displacement, and Energy of Earthquakes

Magnitude Change	Ground Displacement Change[1]	Energy Change
1	10 times	About 32 times
0.5	3.2 times	About 5.5 times
0.3	2 times	About 3 times
0.1	1.3 times	About 1.4 times

[1] Displacement, vertical or horizontal, that is recorded on a standard seismograph.

U.S. Geological Survey. 2000. *Earthquakes, Facts and Statistics.* http://neic.usgs.gov. Accessed 1/3/00.

several hundred thousand. In 1985, an earthquake originating beneath the Pacific Ocean off Mexico (M 8.1) caused 10,000 deaths in Mexico City, several hundred kilometers from the source. Exactly 1 year after the Northridge earthquake, the January 17, 1995, Kobe, Japan, earthquake (M 7.2) killed more than 5,000 and injured 27,000 people, while destroying 100,000 buildings and causing over $100 billion in property damages (**Figure 6.2a**). The January 26, 2001, Gujarat, India, earthquake (M 7.7) killed as many as 30,000 people, injured 166,000, damaged or destroyed about 1 million homes, and left 600,000 people homeless. An earthquake on October 8, 2005, of M 7.6, struck northern Pakistan. Although the epicenter was in Pakistan, extensive damage also occurred in Kashmir and India (Figure 6.2b). More than 80,000 people were killed and more than 30,000 buildings collapsed. Entire villages were destroyed, some buried by landslides triggered by the violent shaking. One of the largest continental earthquakes (M 7.9) to strike a highly populated region in the past 100 years occurred in the Sichuan province of China in 2008, killing about 87,500 people. Some villages were completely buried by landslides, and more than 5 million buildings collapsed (Figure 6.2c).[5–7] Finally the 2010 earthquake in Haiti killed about 240,000 people (see case history opening this chapter).

6.3 Earthquake Intensity

A qualitative way of comparing earthquakes is to use the **Modified Mercalli Scale**, which describes 12 divisions of intensity, based on observations concerning the severity of shaking during an earthquake (**Table 6.4**, page 175). Intensity reflects how people perceived the shaking and how structures responded to the shaking. Whereas a particular earthquake has only one magnitude, different levels of intensity may be assigned to the same earthquake at different locations, depending on proximity to the epicenter and local geologic conditions. **Figure 6.3** (page 175) is a map showing the spatial variability of intensity for the 1971 San Fernando earthquake (M 6.6). Such maps, produced from questionnaires sent to residents in the epicentral region after an earthquake, are a valuable, although crude, index of ground shaking.

One of the major challenges during a damaging earthquake is to quickly determine where the damage is most severe. An approach now being used is known as a **shake map** that shows the extent of potential damaging shaking following an earthquake. Data for a shake map are recorded from a dense network of high-quality seismograph stations. When seismic data are received at seismographic stations, the areas with the severest shaking are known within a minute or so after the shaking has ceased. This information is critical for directing an effective emergency

FIGURE 6.2 Earthquake damage
(a) This elevated road collapsed as a result of intense seismic shaking associated with the 1995 Kobe, Japan, earthquake. *(Haruyoshi Yamaguchi/Sygma/Corbis)* (b) Collapsed buildings, Balakot, Pakistan, from a M 7.6 earthquake in 2005. *(B.K. Bangash/AP Photo)* (c) Collapsed buildings from a 2008 M 7.9 earthquake in China. *(Greg Baker/AP Photo)*

(a)

(b)

(c)

TABLE 6.4 Modified Mercalli Intensity Scale (abridged)

Intensity	Effects
I	Felt by very few people.
II	Felt by only a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration feels like the passing of a truck.
IV	During the day, felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound; sensation like heavy truck striking building; standing motor cars rock noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, and so on broken; a few instances of cracked plaster; unstable objects overturned; disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage is slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures; panel walls thrown out of frame structures; fall of chimneys, factory stacks, columns, monuments, walls; heavy furniture overturned; sand and mud ejected in small amounts; changes in well water; disturbs persons driving cars.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings are shifted off foundations. Ground cracked conspicuously. Underground pipes are broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water is splashed over banks.
XI	Few if any (masonry) structures remain standing. Bridges are destroyed. Broad fissures are formed in ground. Underground pipelines are taken out of service. Earth slumps and land slips on soft ground occurs. Train rails are bent.
XII	Damage is total. Waves are seen on ground surfaces. Lines of sight and level distorted. Objects are thrown upward into the air.

From Wood and Neuman, 1931, by U.S. Geological Survey, 1974, *Earthquake Information Bulletin* 6(5):28.

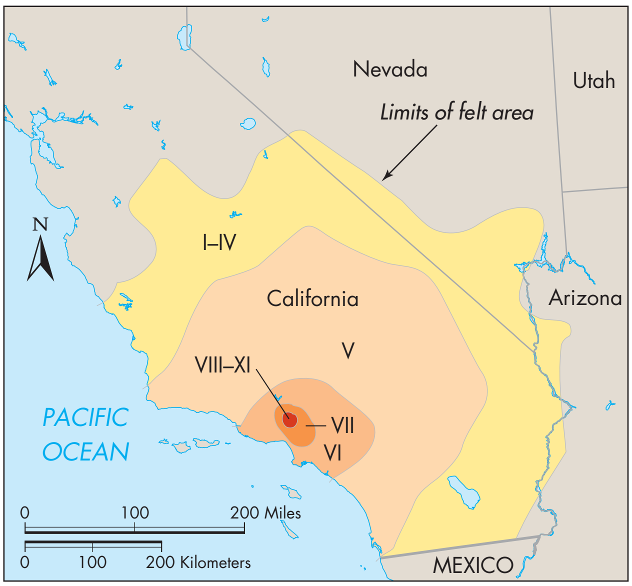
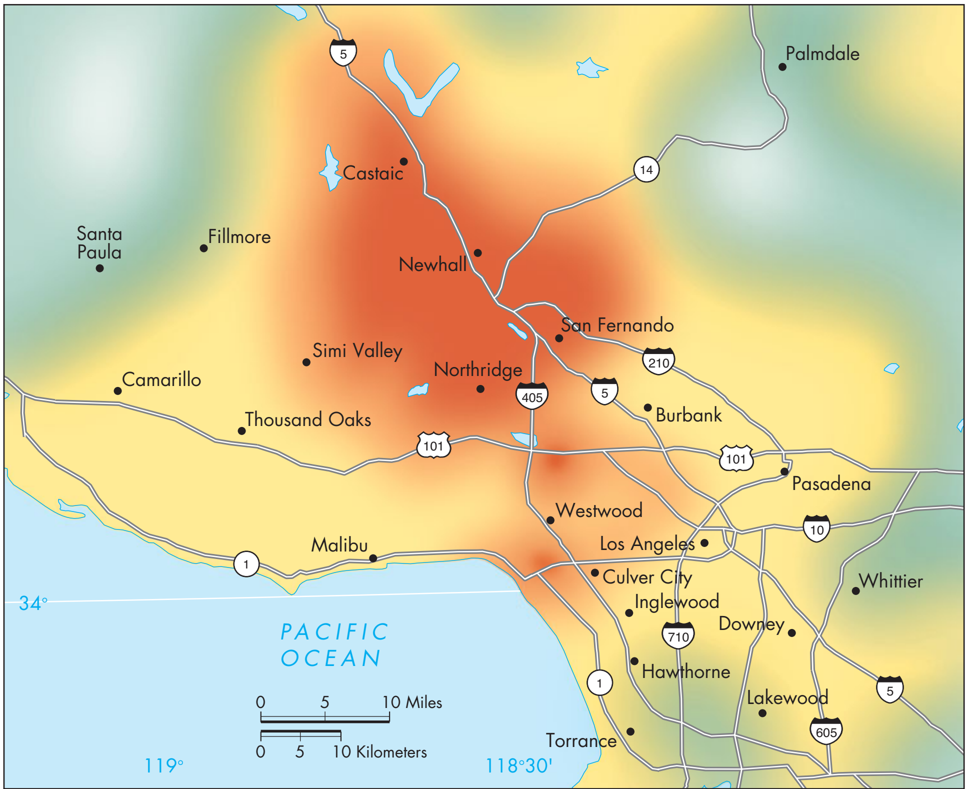


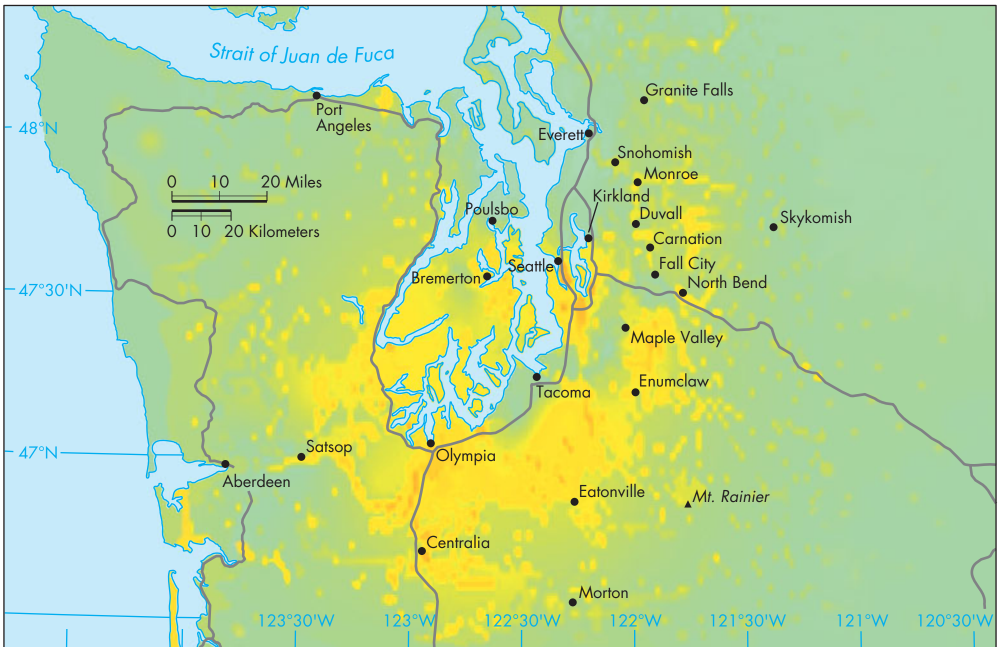
FIGURE 6.3 Intensity of shaking Modified Mercalli intensity map for the 1971 San Fernando Valley, California, earthquake (M 6.6), determined after the earthquake. *(U.S. Geological Survey, 1974,* Earthquake Information Bulletin *6[5])*

response to those areas. The maps in **Figure 6.4** show the shake map for the 1994 Northridge, California, earthquake (M 6.7), and the 2001 M 6.8 Seattle, Washington, earthquake (M 6.8). Notice that the magnitudes of the two earthquakes are very similar, but the intensity of shaking was greater for the Northridge earthquake. The technology to produce and distribute shake maps in the minutes following an earthquake was made available in 2002.[8] The cost of seismographs is small relative to damages from



Instrumental intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	not felt	weak	light	moderate	strong	very strong	severe	violent	extreme
Damage	none	none	none	very light	light	moderate	moderate/heavy	heavy	very heavy

(a)



Instrumental intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	not felt	weak	light	moderate	strong	very strong	severe	violent	extreme
Damage	none	none	none	very light	light	moderate	moderate/heavy	heavy	very heavy

(b)

FIGURE 6.4 Real-time intensity of shaking (a) Shake map for the 1994 Northridge, California, earthquake (M 6.7), determined after the earthquake occurred. *(U.S. Geological Survey, and courtesy of David Wald)* (b) The 2001 Seattle, Washington, earthquake (M 6.8). *(Pacific Northwest Seismograph Network, University of Washington)*

earthquake shaking, and the arrival of emergency personnel is critical in the first minutes and hours following an earthquake, if people in collapsed buildings are to be rescued. The shake map is also very useful in helping locate areas where gas lines and other utilities are likely to be damaged. Clearly, the use of this technology, especially in urban areas vulnerable to earthquakes, is a very desirable component of our preparedness for earthquakes.

6.4 Plate Boundary Earthquakes

California, which straddles two lithospheric plates that are moving past one another, experiences frequent damaging earthquakes. The 1989 Loma Prieta earthquake (M 7.1) on the San Andreas fault system south of San Francisco killed 62 people and caused \$5 billion in property damage. Neither the Loma Prieta earthquake nor the Northridge earthquake (M 6.7) was considered a great earthquake. It has been estimated that a great earthquake, occurring today in a densely populated part of southern California, could inflict \$100 billion in damage and kill several thousand people. Thus, the Northridge quake, as terrible as it was, was not the anticipated "big one." Given that earthquakes have the proven potential for producing a catastrophe, earthquake research is primarily dedicated to understanding earthquake processes. The more we know about the probable location, magnitude, and effects of an earthquake, the better we can estimate the damage that is likely to occur and make the necessary plans for minimizing loss of life and property.

Interplate earthquakes are those between two plates, initiated near plate boundaries and producing nearly continuous linear or curvilinear zones in which most seismic activity takes place (**Figure 6.5**). Most large U.S. earthquakes are interplate earthquakes in the West, particularly near the North American and Pacific plate boundaries (Table 6.1). However, large damaging *intraplate earthquakes*, located within a single plate, can occur far from plate boundaries.

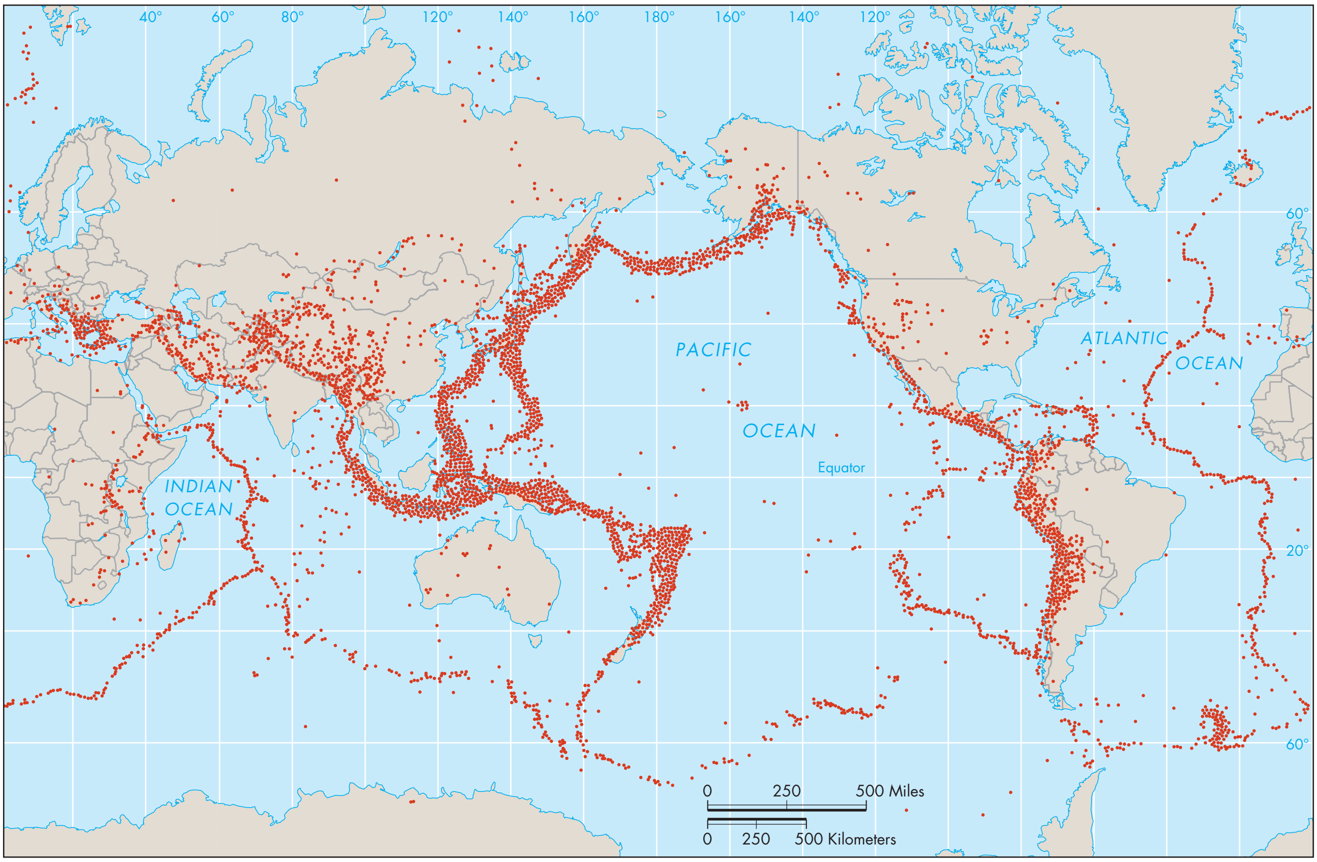


FIGURE 6.5 Earthquakes at plate boundaries Map of global seismicity (1963–1988), delineating plate boundaries (earthquake belts). Red dots represent individual earthquakes. For the locations and names of Earth's tectonic plates, refer to Figure 2.3. *(Courtesy of National Earthquake Information Center)*

6.5 Intraplate Earthquakes

Intraplate earthquakes with M 7.5+ that occurred in the winter of 1811–1812 in the central Mississippi Valley nearly destroyed the town of New Madrid, Missouri, and they killed an unknown number of people. These earthquakes rang church bells in Boston! Seismic shaking produced intense surface deformation over a wide area from Memphis, Tennessee, north to the confluence of the Mississippi and Ohio Rivers. During the earthquakes, forests were flattened; fractures in the ground opened so wide that people had to cut down trees to cross them; and land sank several meters in some areas, causing flooding. It was reported that the Mississippi River actually reversed its flow during shaking. The earthquakes occurred along a seismically active structure known as the New Madrid seismic zone, which underlies the geologic structure known as the Mississippi River Embayment (Figure 6.6). The embayment is a downwarped area of Earth's crust, where the lithosphere is relatively weak. The recurrence interval, or time between events, for major earthquakes in the embayment is estimated to be about 500 years.[9,10] Even in this "stable" interior of the North American plate, the possibility of future damage demands that the earthquake hazard in the area be considered when facilities, such as power plants and dams, are being designed and built. It is believed that the New Madrid seismic zone is a young—perhaps less than 10,000 years old—zone of deformation. The rate of uplift is sufficient to produce significant topographic relief over a period of several hundred thousand years. The fact that the topography of the uplifted region in the Mississippi River floodplain area is very minor supports the hypothesis that this is a very young fault system or one that has been recently reactivated. The New Madrid seismic zone is capable of producing great earthquakes and is the object of intensive research.

FIGURE 6.6a New Madrid seismic zone The location of this zone is thousands of kilometers from the nearest plate boundary (red lines).

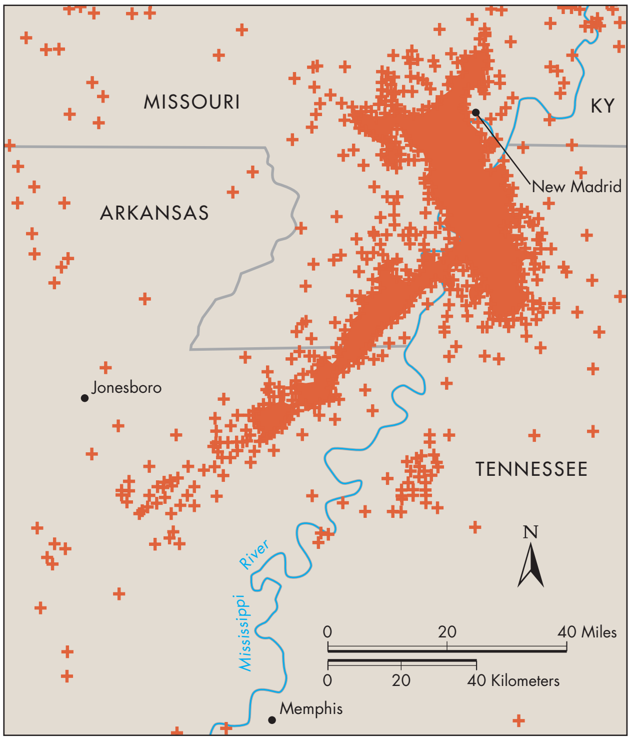


FIGURE 6.6b Earthquake-prone region The New Madrid seismic zone is the most earthquake-prone region in the United States east of the Rocky Mountains. Locations of recorded minor earthquakes since 1974 are shown as crosses. *(U.S. Geological Survey)*

Another large damaging intraplate earthquake (M 7.5) occurred on August 31, 1886, near Charleston, South Carolina. The earthquake killed about 60 people and damaged or destroyed most buildings in Charleston. Effects of the earthquake were reported at distances exceeding 1,000 km (620 mi).

Intraplate earthquakes in the eastern United States are generally more damaging and felt over a

much larger area than are similar-magnitude earthquakes in California. The reason is that the rocks in the eastern United States are generally stronger and less fractured and can more efficiently transmit earthquake waves than can rocks in the west.

6.6 Earthquake Processes

Our discussion of global tectonics established that Earth is a dynamic, evolving system. Earthquakes are a natural consequence of the processes that form the ocean basins, continents, and mountain ranges of the world. Most earthquakes occur along the boundaries of lithospheric plates (Figure 6.5).

Faulting

The process of fault rupture, or *faulting*, can be compared to sliding two rough boards past one another. Friction along the boundary between the boards, analogous to a fault plane, may temporarily slow their motion, but rough edges break off, and motion occurs at various places along the plane. For example, lithospheric plates that are moving past one another are slowed by friction along their boundaries. As a result, rocks along the boundary undergo strain, or deformation, resulting from stress produced by the movement. When stress on the rocks exceeds their strength, the rocks rupture, forming a fault and producing an **earthquake**. A **fault** is a fracture or fracture system along which rocks have been displaced; that is, one side of the fracture or fracture system has moved relative to the other side. The long-term rate of movement is known as the *slip rate* and is often recorded as millimeters per year (mm/yr) or meters per 1,000 years (m/ky). During a major to great earthquake, displacements of several meters may suddenly occur along a fault. When a rupture begins, it starts at the focus and then grows or propagates up, down, and laterally along the fault plane during an earthquake (see Figure 6.1). The sudden rupture of the rocks produces shock waves called earthquake waves, or *seismic waves*, that shake the ground. In other words, the pent-up energy of the strained rocks is released in the form of an earthquake. Faults are, therefore, *seismic sources*, and identifying them is the first step in evaluating the risk of an earthquake, or seismic risk, in a given area.

Fault Types

The major types of faults, based on the direction, or sense of the relative displacement, are shown on **Figure 6.7**. A *strike-slip fault* is a fault in which the sides of the fault are displaced horizontally; a strike-slip fault is called *right-lateral* if the right-hand side moves toward you as you sight, or look along, the fault line, and *left-lateral* if the left-hand side moves toward you. A fault with vertical displacement is referred to as a *dip-slip fault*. A dip-slip fault may be a *reverse fault* or a *normal fault*, depending on the geometry of the displacement. Geologists use interesting terminology to distinguish reverse and normal faults. Notice in Figure 6.7 that there are two blocks separated by the fault plane. One way to remember the terminology for the two blocks is to imagine you are walking up the fault plane, like walking up a hill. The block you would be standing on is called the foot-wall, and the other block is called the hanging-wall. If the fault displacement is such that the hanging-wall moves up relative to the foot-wall, the fault is called a *reverse fault*. When the fault plane of a reverse fault has an angle of less than 45 degrees, it is called a *thrust fault*. If the hanging-wall moves down relative to the foot-wall, the fault is called a *normal fault*. Reverse and thrust fault displacement are associated with crustal shortening, whereas normal fault displacement is associated with crustal extension.

The faults shown in Figure 6.7 generally produce surface displacement or rupture. However, there are also *buried faults*, usually associated with folded rocks. Displacement and rupture of buried faults do not propagate to the surface, even in large earthquakes, as was the case with the Northridge earthquake.

The relationship of a buried reverse fault to rock folding is shown in **Figure 6.8** (page 181). Shortening of a sequence of sedimentary rocks has produced folds, called anticlines and synclines. *Anticlines* are arch-shaped folds; *synclines* are bowl-shaped folds. In this illustration, anticlines form ridges, and synclines form basins at the surface of the ground. Notice that, in the cores of two of the anticlines on the right, buried faulting has occurred. Faulting during earthquakes causes anticlinal mountains to be uplifted, whereas subsidence, or sinking of the ground surface, may occur in synclinal valleys.

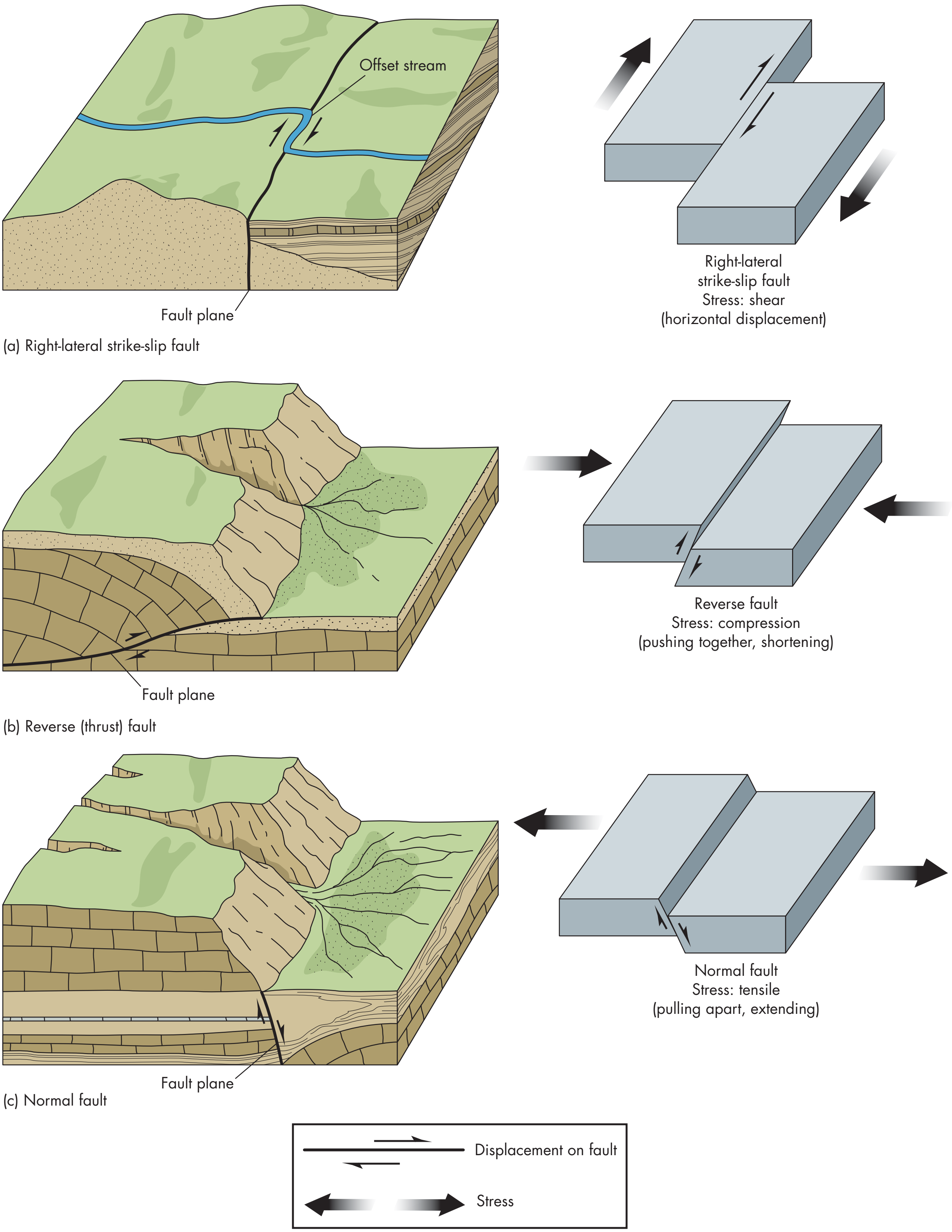


FIGURE 6.7 Faulting changes the land Types of fault movement and effects on the landscape, based on the sense of motion relative to the fault.

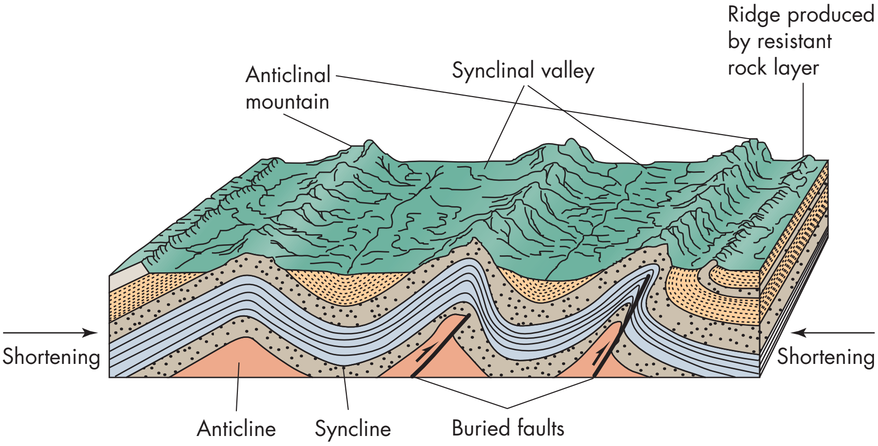


FIGURE 6.8 Buried faults Block diagram illustrating several types of common folds and buried reverse faults with possible surface expressions, such as anticlinal mountains and synclinal valleys. *(Modified after Lutgens, F., and Tarbuck, E. 1992.* Essentials of Geology, *4th ed. New York: Macmillan)*

Until recently, it was thought that most active faults could be mapped because their most recent earthquake would cause surface rupture. Discovering that some faults are buried and that rupture does not always reach the surface has made it more difficult to evaluate the earthquake hazard in some areas. (See Case History: Northridge, 1994.)

Fault Zones and Fault Segments

Faults almost never occur as a single rupture. Rather, they form **fault zones**, which are a group of related faults roughly parallel to each other in map view. They often partially overlap or form braided patterns. Fault zones vary in width, ranging from a meter or so to several kilometers.

Most long faults or fault zones, such as the San Andreas fault zone, are *segmented*, with each segment having an individual history and style of movement. An **earthquake segment** is defined as those parts of a fault zone that have ruptured as a unit during historic and prehistoric earthquakes. Rupture during an earthquake generally stops at the boundaries between two segments; however, major to great earthquakes may involve several segments of the fault. Rupture length from large earthquakes is measured in tens of kilometers. It is the *earthquake segment* that is often useful in estimating the magnitude of a future earthquake.

When the earthquake history of a fault zone is unknown, the zone may be divided into segments, based on differences in morphology or geometry. However, from the point of view of earthquake-hazard evaluation, it is preferable to define fault segments according to their history, which includes both historic seismic activity and *paleoseismicity* (prehistoric seismic activity). *Paleoseismology* is the study of prehistoric earthquakes from the geologic environment. The geologic processes that govern **fault segmentation** and generation of earthquakes on individual segments are the subject of active research.

Active Faults

Most geologists consider a particular fault to be an *active fault* if it can be demonstrated to have moved during the past 10,000 years, the Holocene epoch. The Quaternary period, spanning approximately the past 2.6 million years, is the most recent period of geologic time, and most of our landscape has been produced during that time (see Table 1.1). Fault displacement that has occurred during the Pleistocene epoch of the Quaternary period, approximately 2.6 million to 10,000 years ago, but not in the Holocene, is classified as *potentially active* (**Table 6.5**).

Faults that have not moved during the past 2.6 million years are generally classified as *inactive*. However, we emphasize that it is often difficult to prove the activity of a fault in the absence of easily measured phenomena, such as historical earthquakes. Demonstrating that a fault is active may require determining the past earthquake history, or *paleoseismicity*, on the basis of the geologic record. This determination involves identifying faulted Earth materials and determining when the most recent displacement occurred.

For seismic zoning, the state of California defines an **active fault** as a fault that has moved in the

TABLE 6.5 Terminology Related to Recovery of Fault Activity

GEOLOGIC AGE			Years Before Present	Fault Activity
Era	Period	Epoch		
	Quaternary	Historic	200	Active
		Holocene	10,000	
Cenozoic		Pleistocene	2,600,000	Potentially active
	Tertiary	Pre-Pleistocene	65,000,000	Inactive
	Pre-Cenozoic time		4,500,000,000	
	Age of Earth			

After California State Mining and Geology Board Classification, 1973.

last 10,000 years. However, other agencies have more conservative definitions for fault activity. For example, the U.S. Nuclear Regulatory Commission, when considering seismic safety for nuclear power plants, defines a fault as *capable* if it has moved at least once in the past 50,000 years or more than once in the last 500,000 years. These criteria provide a greater safety factor, reflecting increased concern about the risk inherent in the siting of nuclear power plants.

Fault activity involves two important and interrelated concepts: slip-rates on faults and recurrence intervals (repeat times) of earthquakes. **Slip rate** on a fault is defined as the ratio of slip (displacement) to the time interval over which that slip occurred. For example, if a fault has displacement of 1 m during a time interval of 1,000 years, the slip rate is 1 mm per year.

The average **recurrence interval** of earthquakes on a particular fault may be determined by three methods:

1. *Paleoseismic data:* This method involves averaging the time intervals between earthquakes recorded in the geologic record.
2. *Slip rate:* This method involves assuming a given displacement per event and dividing that number by the slip rate. For example, if the average displacement per event were 1 m and the slip rate 2 mm per year, then the average recurrence interval would be 500 years.
3. *Seismicity:* This method involves using historical earthquakes and averaging the time intervals between events.

Defining slip rate and recurrence interval is easy, and the calculations seem straightforward. However, the concepts of slip rate and recurrence interval are far from simple. Fault slip rates and recurrence intervals tend to change over time, casting suspicion on average rates. For example, it is not uncommon for earthquake events to cluster in time and then be separated by long periods of low activity. Thus, both slip rate and recurrence interval will vary according to the time interval for which data is available.

Methods of Estimating Fault Activity. Various methods are used to estimate *fault activity*, which includes both historic and prehistoric earthquakes. Paleoseismicity can be estimated by investigating landforms produced or displaced by faulting. Features such as offset streams, sag ponds, linear ridges, and fault scarps (i.e., steep slopes or cliffs produced by fault movement) may indicate recent faulting. However, care must be exercised in interpreting these landforms because some of them may have a complex origin.

The study of soils can also be useful in estimating the activity of a fault. For example, soils on opposite sides of a fault may be of similar age or quite dissimilar age, thus establishing a relative age for the displacement.

Case History

Northridge, 1994

The 1994 Northridge earthquake that struck the Los Angeles area on January 17 was a painful wake-up call to southern Californians. The earthquake killed 57 people and caused about $40 billion in property damage. Several sections of freeways were heavily damaged, as were parking structures and more than 3,000 buildings (Figure 6.A). The Northridge earthquake is one in a series of moderate-sized earthquakes that have recently occurred in southern California.

The rupture of rocks that produced the Northridge earthquake was initiated on a steep buried fault, at a depth of approximately 18 km (11 mi). The rupture quickly propagated upward (northward and westward) but did not reach the surface, stopping at a depth of several kilometers. At the same time, the rupture progressed laterally, in a mostly westward direction, 20 km (12.5 mi). The geometry of the fault movement is shown in Figure 6.B. The movement produced uplift and folding of part of the Santa Susana Mountains, a few kilometers north of Northridge.[11]

The Northridge earthquake terrified people, especially children. The shaking, which lasted about 15 seconds, was intense; people were thrown out of bed, objects flew across rooms, chimneys tumbled, walls cracked, and Earth groaned and roared with each passing earthquake wave. When the shaking stopped, people had little time to recover before strong aftershocks started.

FIGURE 6.A Earthquake in Los Angeles urban region Damage from the 1994 Northridge, California, earthquake. (a) A parking structure. *(R. Forrest Hopson)* (b) Damage to the Kaiser Permanente Building. *(A. G. Sylvester)*

(a)

(b)

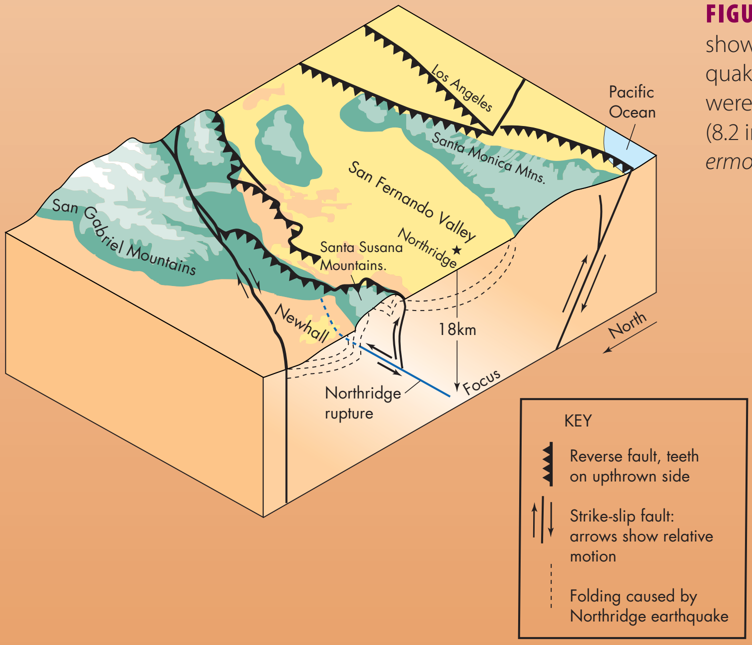


FIGURE 6.B Details of an earthquake Block diagram showing the fault that produced the 1994 Northridge earthquake. During the earthquake, the Santa Susana Mountains were folded, uplifted 38 cm (15 in.), and moved 21 centimeters (8.2 in.) to the northwest. *(Courtesy of Pat Williams, Lawrence Livermore Laboratory)*

Prehistoric earthquake activity sometimes can be dated radiometrically, providing a numerical date if suitable materials can be found. For example, radiocarbon dates from faulted sediments have been used to calculate slip rates and estimate recurrence intervals of large earthquakes.

Tectonic Creep

Some active faults exhibit **tectonic creep**, that is, gradual displacement that is not accompanied by felt earthquakes. The process can slowly damage roads, sidewalks, building foundations, and other structures. Tectonic creep has damaged culverts under the football stadium of the University of California at Berkeley, and periodic repairs have been necessary as the cracks have developed. Movement of approximately 3.2 cm (1.3 in.) was measured in a period of 11 years. More rapid rates of tectonic creep have been recorded on the Calaveras fault zone, a segment of the San Andreas fault, near Hollister, California. At one location, a winery situated on the fault is slowly being pulled apart at about 1 cm (0.4 in.) per year (**Figure 6.9**). Damages resulting from tectonic creep generally occur along narrow fault zones that are subject to slow, continuous displacement.

Slow Earthquakes

Slow earthquakes are similar to other earthquakes, in that they are produced by fault rupture. However, with a slow earthquake, the rupture, rather than being nearly instantaneous, can last from days to months. The moment magnitude of slow earthquakes can be in the range of 6 to 7 because a large area of rupture is often involved, although the amount of slip is generally small (e.g., a centimeter or so). Slow earthquakes are a newly recognized fundamental Earth process. They are recognized through analysis of continuous geodetic measurement or GPS, similar to the devices that are used in automobiles to identify location. These instruments can differentiate horizontal movement in the millimeter range and have been used to observe surface displacements from slow earthquakes. When slow earthquakes occur frequently, such as every year, their total contribution to changing the surface of the Earth to produce mountains over geologic time may be significant.[12]

6.7 Earthquake Shaking

Three important factors determine the shaking you will experience during an earthquake: (1) earthquake magnitude, (2) your distance from the epicenter, and (3) local soil and rock conditions. If an earthquake is of moderate magnitude (M 5 to 5.9) or larger, then strong motion or shaking may be expected. It is the strong motion from earthquakes that cracks the ground and makes Earth "rock and roll," causing damage to buildings and other structures.

Types of Seismic Waves

Some of the seismic waves generated by fault rupture travel within Earth, and others travel along the surface. The two types of seismic waves that travel with a velocity of several kilometers per second through rocks are primary (P) and secondary (S) waves (see **Figure 6.10a,b**, page 186).

P waves, also called *compressional waves*, are faster than S waves and can travel through solid, liquid, and gaseous materials (see Figure 6.10a). The velocity of P waves through liquids is much slower. Interestingly, when P waves are propagated into the atmosphere, they are detectable to the human ear. This fact explains the observation that people sometimes *hear* an earthquake before they feel the shaking caused by the arrival of the slower surface waves.[13]

S waves, also called *shear waves*, can travel only through solid materials. Their speed through rocks, such as granite, is approximately one-half that of P waves. S waves produce an up-and-down or side-to-side motion at right angles to the direction of wave propagation, similar to the motion produced in a clothesline by pulling it down and letting go (see Figure 6.10b). Because liquids cannot spring back when subjected to this type of motion, called sideways shear, S waves cannot move through liquids.[13]

When seismic waves reach the surface, complex **surface waves** (R waves) are produced. Surface waves, which move along Earth's surface, travel more slowly than either P or S waves and cause much of the

(a)

(b)

FIGURE 6.9 Tectonic creep (a) This concrete culvert at the Almaden Vineyards in Hollister, California, is being split by creep on the San Andreas fault. *(James A. Sugar/NGS Image Collection)* (b) Creep along the Hayward fault (a branch of the San Andreas fault) is slowly deforming the football stadium at the University of California at Berkeley from goalpost to goalpost. *(Courtesy of Richard Allen)*

earthquake damage to buildings and other structures. Damage occurs because surface waves have a complex horizontal and vertical ground movement or rolling motion that may crack walls and foundations of buildings, bridges, and roads. An important surface wave is the R wave, shown in Figure 6.10c. The rolling motion moves in the direction opposite to that of the wave propagation (direction wave is moving) and the vertical motion, or amplitude, is at right angles to the direction of propagation.

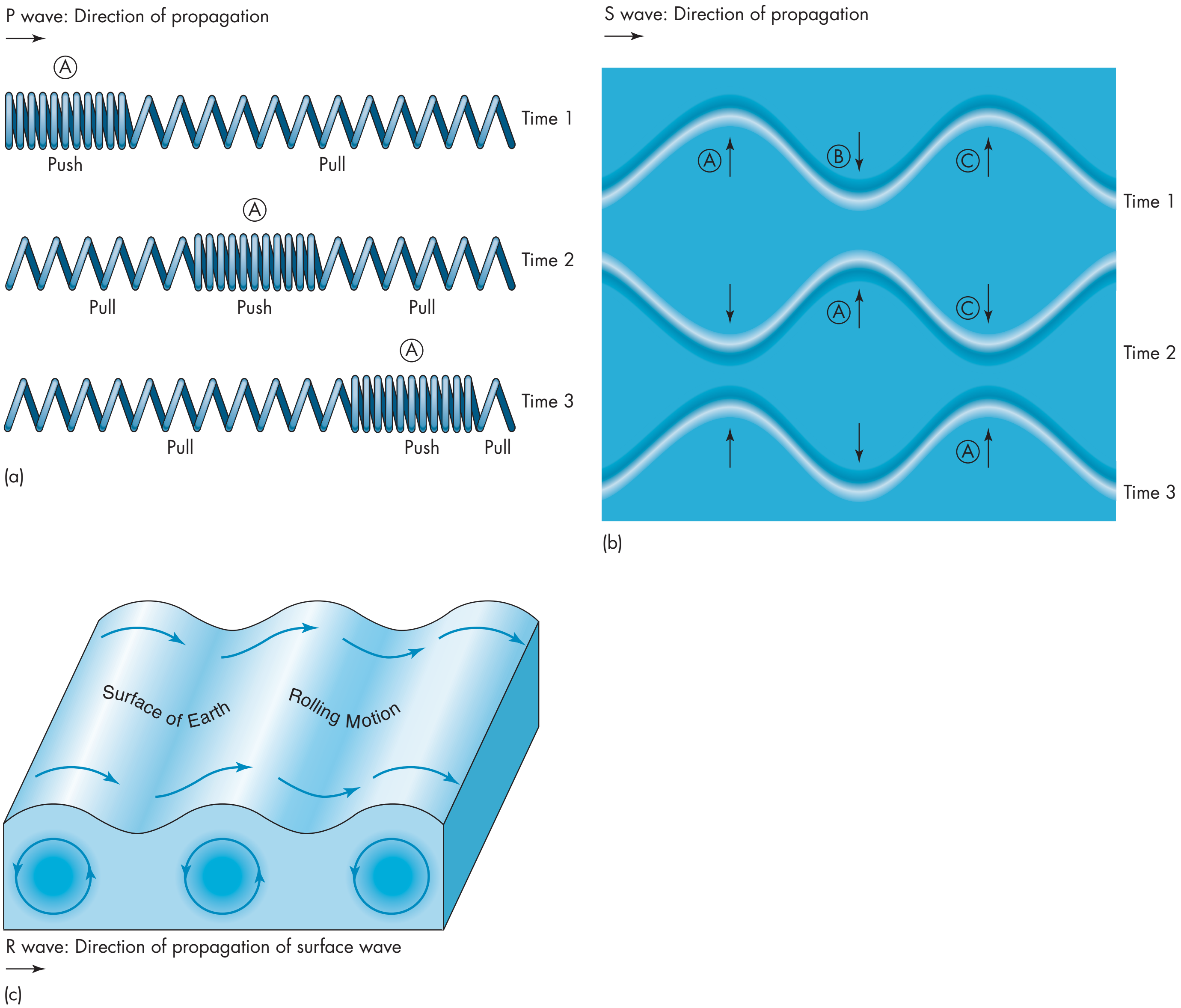


FIGURE 6.10 Seismic waves Idealized diagram showing differences between P waves and S waves. (a) Visualize the P wave as dilation (pulling apart) and contraction (pushing together) of the rings of a Slinky plastic spring. If you extend it about 3 m (about 10 ft) horizontally on a flat surface and then push from the left end, the zone of compression (i.e., contraction) will propagate to the right, as shown. The rate of propagation of P waves through rocks such as granite is about 6 km/sec (3.7 mi/sec). Through liquids, P waves move much slower, about 1.5 km/sec (0.9 mi/sec) through water. (b) To visualize S waves, stretch a rope about 7 m (about 23 ft) between two chairs, or use a clothesline if you have one. Pull up the left end and then release it; the wave will propagate to the right, in this case, up and down. Displacement for S waves is at right angles to the direction of wave propagation, just the opposite of P wave displacements that push and pull in the same direction as the wave propagates. Points A, B, and C are the positions of a specific part of the wave at different times. S waves travel through rocks, such as granite, approximately 3 km/sec (1.9 mi/sec). They cannot travel through liquids. (c) Surface, or R, waves. Notice that the vertical motion is at right angles to the direction of wave propagation, and that the elliptical motion is opposite to the direction of propagation. Surface waves are often the most damaging of the seismic waves.

Seismograph

A *seismogram* is a written or digital record of an earthquake. In written form, it is a continuous line that shows vertical or horizontal Earth motions received at a seismic recording station and recorded by a seismograph. The components of a simple seismograph are shown in **Figure 6.11a**, and a photograph of an older seismograph is shown in Figure 6.11b. An idealized written record, or seismogram, is shown in Figure 6.11c. Notice that, for Figure 6.11c,

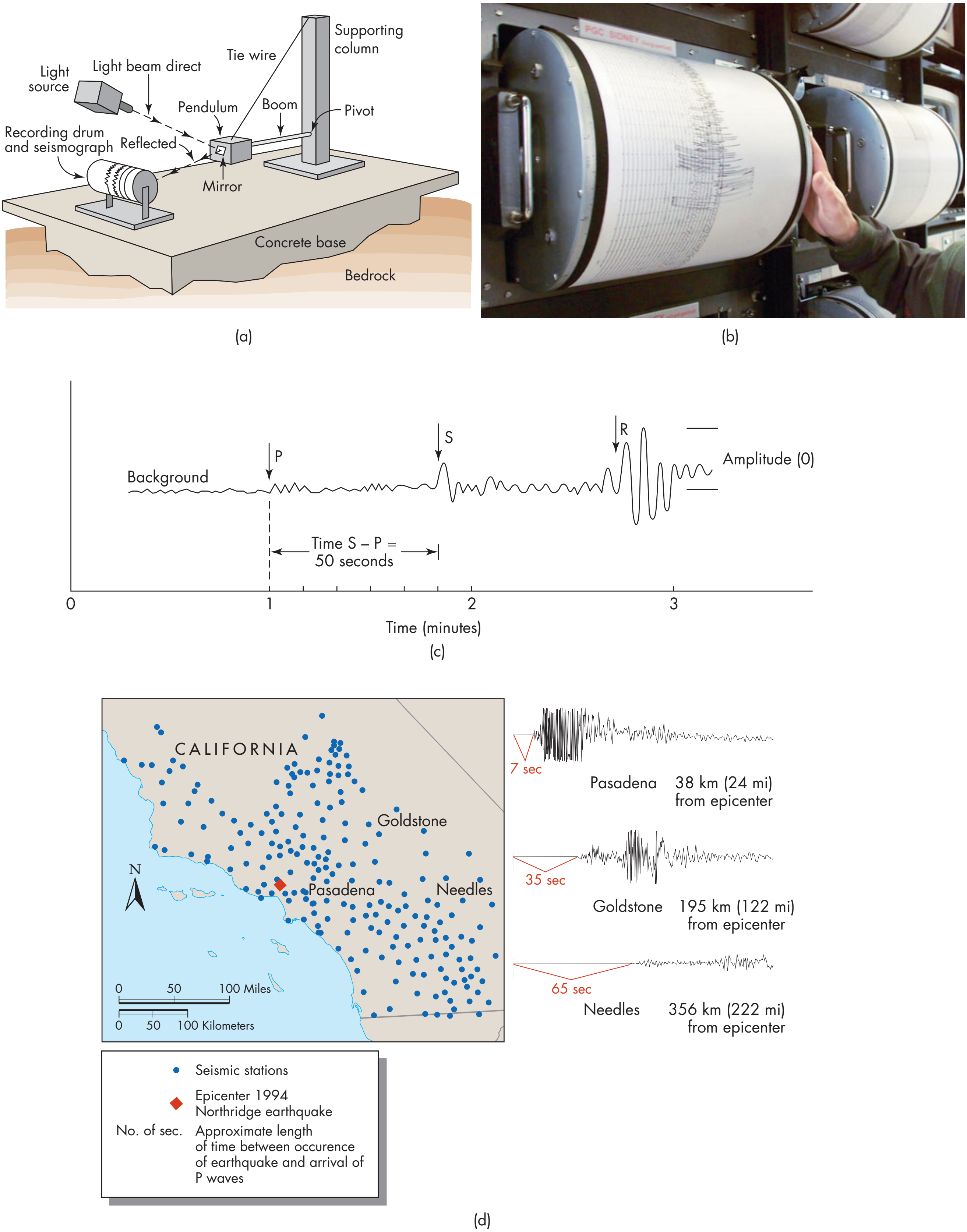


FIGURE 6.11 Seismograph (a) Simple seismograph, showing how it works. (b) Modern seismograph at the Pacific Geoscience Centre in Canada. The earthquake is the February 28, 2001, Seattle earthquake (M 6.8). *(Ian McKain/AP Photo)* (c) Idealized seismogram for an earthquake. The amplitude of the R (surface) waves is greater than that of P and the S waves. The S – P time of 50 seconds tells us that the earthquake epicenter was about 420 km (261 mi) from the seismograph. (d) Differences in arrival time and amount of shaking at three seismic stations located from 38 to 356 km (24 to 222 mi) from the 1994 Northridge, California, earthquake. Notice that, with distance, the time of arrival of shaking increases, and the amplitude of shaking decreases. *(Modified from Southern California Earthquake Center)*

the P waves arrive 50 seconds before the S waves and about 1 minute 40 seconds before the R waves. R waves have the largest amplitude and often cause the most damage to buildings.

The effect of distance on the seismogram is shown in Figure 6.11d for the 1994 M 6.7 Northridge, California, earthquake. Three seismographs, from close to the epicenter at Pasadena (38 km [24 mi]) to far away at Needles (356 km [221 mi]), are shown. The shaking starts with the arrival of the P wave. Notice that the shaking arrives sooner and is more intense at Pasadena than at Needles.

The difference in the arrival times shown by seismograms (S – P) can be used to locate the epicenter of an earthquake. Locating an epicenter requires at least three seismograms from three locations. For example, the S – P value of 50 seconds on Figure 6.11c suggests that the distance between the epicenter and the seismograph was about 420 km (261 mi). This is calculated algebraically, using the S – P value and the velocity for P and S waves mentioned earlier; however, this calculation is beyond the scope of our discussion. Although we now know that the epicenter was about 420 km (261 mi) from the seismograph, this distance could be in any direction. When the records from seismographs from numerous seismic stations are analyzed using computer models, the epicenter for an earthquake can be located. The model is used to calculate the travel times of seismic waves to each seismograph from various depths of focus (**Figure 6.12**). Distances and depths to the focus are adjusted to provide the best fit of the data from all the seismographs. By a process of approximation, the location of the epicenter and depth to the focus are determined.

Frequency of Seismic Waves

An important characteristic of earthquakes and their seismic waves is their frequency, measured in cycles per second, or hertz (Hz). To understand wave frequency, visualize water waves traveling across the surface of the ocean, analogous to seismic waves. If you are at the end of a pier and record the time when each wave peak moves by you toward shore, the average time period between wave peaks is the *wave period* and is usually measured in seconds. Consider the passing of each wave by you to be one cycle. If one wave passes the end of the pier on its way toward the shore every 10 seconds, the wave period is 10 seconds, and there are 6 waves per minute. The frequency of the waves in cycles per second is 1 cycle divided by 10 seconds, or 0.1 Hz. Returning to earthquake waves, most P and S waves have frequencies of 0.5 to 20 Hz, or 0.5 to 20 cycles per second. Surface waves have lower frequencies than P and S waves, often less than 1 Hz.

Why is the wave frequency important? During an earthquake, seismic waves with a wide range of frequencies are produced, and intense ground motion near the epicenter of a large earthquake is observed. High-frequency shaking causes low buildings to vibrate, and low-frequency shaking causes tall buildings to vibrate. It is the vibrating or shaking that damages buildings. Two points are important in understanding the shaking hazard: (1) Near the epicenter, both shorter buildings and taller buildings

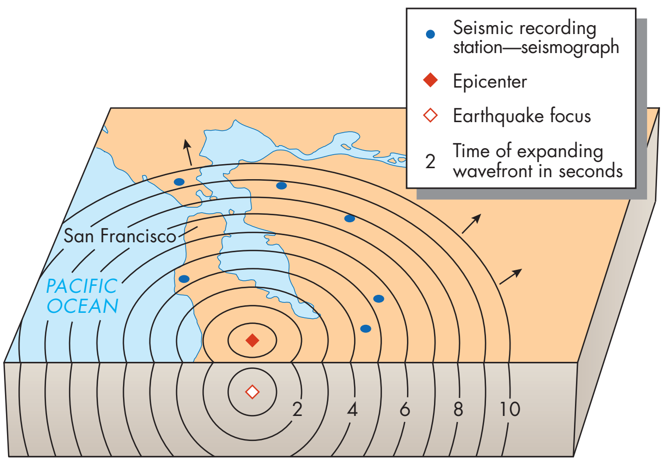


FIGURE 6.12 Locating an earthquake Idealized diagram of San Francisco, California, region, with expanding wavefront of seismic waves from the focus of an earthquake. The arrival of waves at seismic recording stations may be used to mathematically calculate the location of the epicenter and its depth of focus. *(U.S. Geological Survey)*

may be damaged by high- and low-frequency seismic waves. (2) With increasing distance from the epicenter, the high-frequency waves are weakened or removed by a process called *attenuation*. Rapid shaking dies off quickly with distance. As a result, nearby earthquakes are often described as "jolting" and faraway earthquakes as "rolling." Low-frequency seismic waves of about 0.5 to 1.0 Hz can travel long distances without much attenuation. Therefore, they can damage tall buildings far from the epicenter. This fact has importance in planning to reduce earthquake damages and loss of life. Tall buildings need to be designed to withstand seismic shaking, even if they are located hundreds of kilometers from large faults that are capable of producing strong to great earthquakes.

Material Amplification

Different Earth materials, such as bedrock, alluvium (sand and gravel), and silt and mud, respond differently to seismic shaking. For example, the intensity of shaking or strong ground motion of unconsolidated sediments may be much more severe than that of bedrock. Figure 6.13 shows how the *amplitude* of shaking, or the vertical movement, is greatly increased in unconsolidated sediments, such as silt and clay deposits. This effect is called **material amplification**.

The Mexico City earthquake (M 8.1) demonstrated that buildings constructed on materials likely to accentuate and increase seismic shaking are extremely vulnerable to earthquakes, even if the event is centered several hundred kilometers away. Although seismic waves originating offshore initially contained many frequencies, those arriving at the city were low-frequency waves of about 0.5 to 1.0 Hz. It is speculated that, when seismic waves struck the lake beds beneath Mexico City, the amplitude of shaking may have increased at the surface by a factor of 4 or 5. Figure 6.14 shows the geology of the city and the location of the worst damage. The intense regular shaking caused buildings to sway back and forth, and, eventually, many of them pancaked as upper stories collapsed onto lower ones.[14]

The potential for amplification of surface waves to cause damage was again demonstrated with tragic results during the 1989 Loma Prieta earthquake (M 7.1), which originated south of San Francisco. Figure 6.15 (page 191) shows the epicenter and the areas that greatly magnified shaking. The collapse of a tiered freeway, which killed 41 people, occurred on a section of roadway constructed on bay fill and mud (Figure 6.16, page 192). Less shaking occurred where the freeway was constructed on older, stronger alluvium; in these areas, the structure survived. Extensive damage was also recorded in the Marina district of San Francisco (Figure 6.17, page 192). This area was primarily constructed on bay fill and mud, as well as debris dumped into the bay during the cleanup following the 1906 earthquake.[15]

Directivity

Rupture of rocks on a fault plane starts at a point and radiates, or propagates, from that point. The larger the area of rupture, the larger the earthquake.

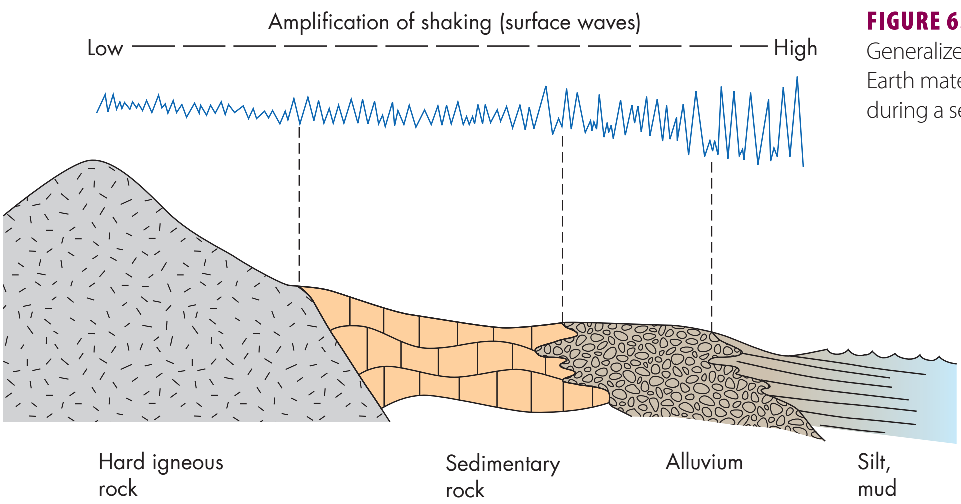
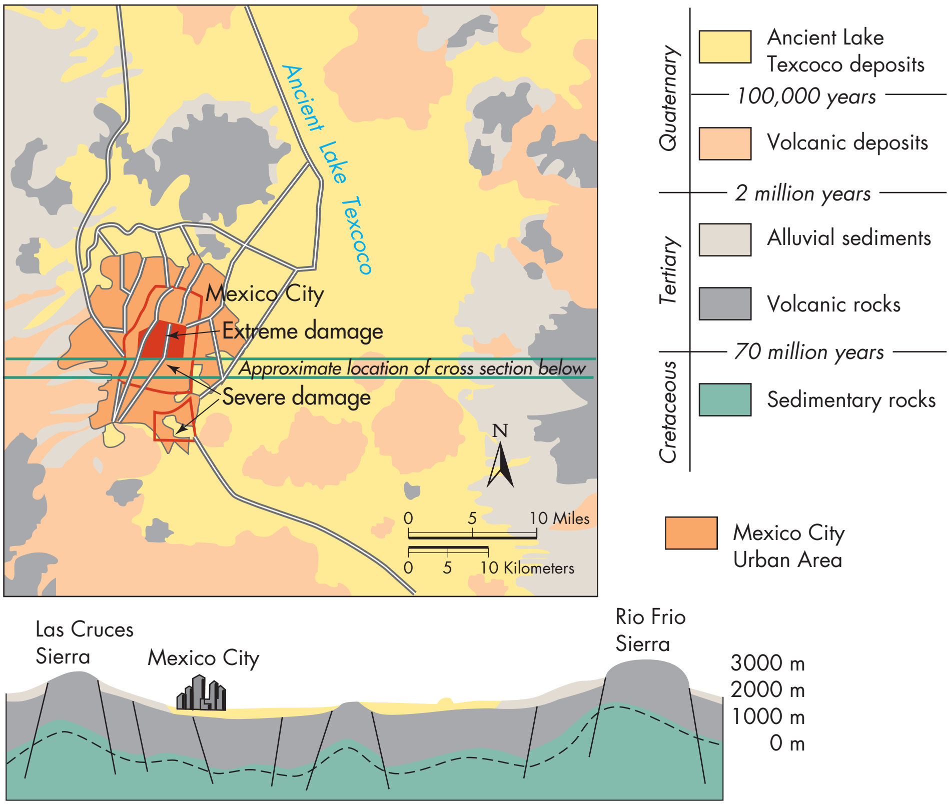


FIGURE 6.13 Amplification of shaking Generalized relationship between near-surface Earth material and amplification of shaking during a seismic event.

FIGURE 6.14 Earthquake damage to Mexico City
(a) Generalized geologic map of Mexico City, showing the ancient lake deposits where the greatest damage occurred. The zone of extreme damage is represented by the solid red area, and the severe damage zone is outlined in red. (b) One of many buildings that collapsed during the 1985 (M 8.1) earthquake. *(Both courtesy of T. C. Hanks and Darrell Herd/USGS)*



(a)

(b)

Directivity, the intensity of seismic shaking increases in the direction of the fault rupture. For example, fault rupture of the 1994 Northridge earthquake was upwards along the fault (north) and to the west, resulting in stronger ground motions from seismic shaking to the northwest (**Figure 6.18**, page 193). The stronger ground motion to the northwest is believed to have resulted from the movement of a block of Earth, the hanging-wall block, upward and to the northwest.[11]

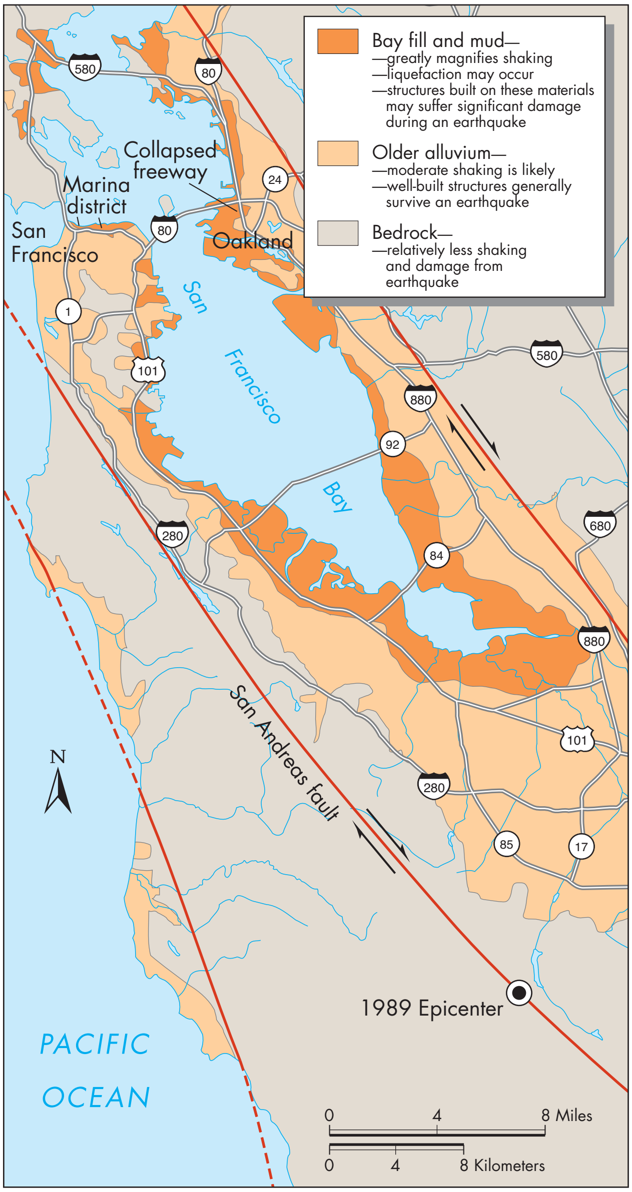
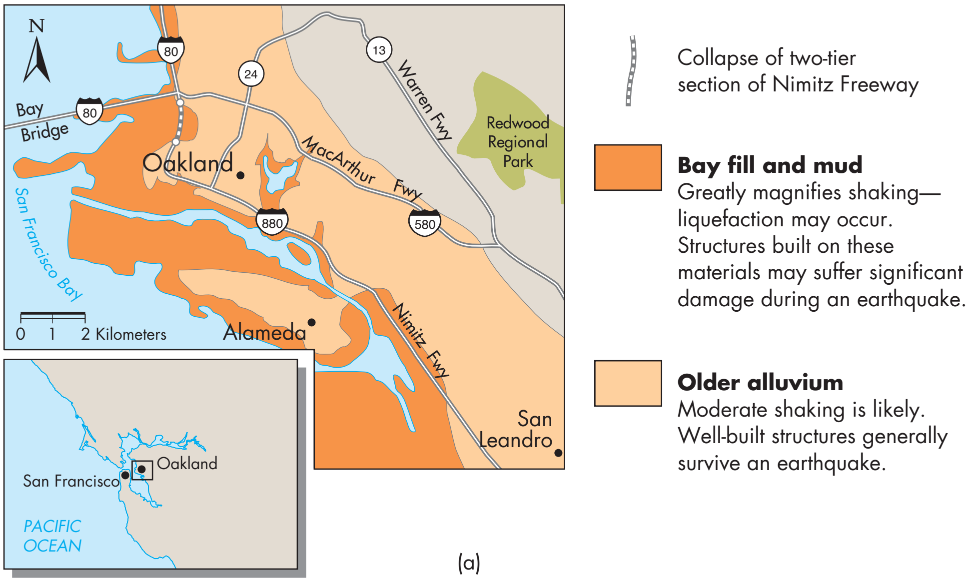


FIGURE 6.15 Loma Prieta earthquake San Francisco Bay region, showing the San Andreas fault and the epicenter of the 1989 earthquake, which had a magnitude of 7.1. The most severe shaking was on bay fill and mud, where a freeway collapsed and the Marina district was damaged. *(Modified after T. Hall. Data from U.S. Geological Survey)*

Ground Acceleration During Earthquakes

Strong ground motion from earthquakes may be described in terms of the speed or velocity at which primary, secondary, and surface waves travel through rocks or across the surface of Earth. In general, these waves move a few kilometers per second. This velocity is analogous to the units used to describe the speed at which you drive a car, for example, 100 km (62 mi) per hour. Earthquake waves, however, travel much faster than cars, at a velocity of about 20,000 km (12,428 mi) per hour, similar to that of the U.S. Space Shuttle when it orbits Earth. Damage to structures from strong ground motion is related to both the amplitude of seismic surface waves and the rate of velocity change of the seismic waves with time. The rate of change of velocity with time is referred to as *acceleration*. You may have learned in physical science that the acceleration due to gravity on Earth is 9.8 meters per second per second (written as 9.8 m/sec^2, or 32 ft/sec^2). This acceleration is known as 1 *g*. If you parachute from an airplane and free fall for several seconds, you will experience the acceleration of gravity (1 *g*), and, by the end of the first second of free fall, your velocity will be 9.8 m/sec. At the end of 2 seconds of free fall, your velocity will be about 20 m/sec, and it will be about 30 m/sec at the end of 3 seconds. This increase, or rate of change, in velocity with time is the acceleration. Earthquake waves cause the ground to accelerate both vertically and horizontally, just as your car accelerates horizontally when you step on the gas pedal. Specially designed instruments, called accelerometers, measure and record the acceleration of the ground during earthquakes. The units of acceleration in earthquake studies are in terms of the acceleration of gravity. If the ground accelerates at 1 *g*, the value is 9.8 m/sec^2. If the acceleration of the ground is 0.5 *g*, the value is roughly 5 m/sec^2. One reason we are interested in acceleration of the ground from earthquakes is that, when engineers design buildings to withstand seismic shaking, the building design criteria are often expressed in terms of a maximum acceleration of the ground, since it is the horizontal acceleration of the ground that causes most damage to buildings. For example, earthquakes with M 6.0 to 6.9, typical magnitudes for strong southern California earthquakes, will produce horizontal accelerations of about 0.3 to 0.7 *g*, with localized values near the epicenter exceeding 1.0 *g*. Horizontal accelerations in excess of about 0.3 *g* cause damage to some buildings, and, at 0.7 *g*, damage is widespread, unless buildings are designed and constructed to withstand strong ground motion. Therefore, if we wish to design buildings to withstand M 6 to 6.9 earthquakes, we need to conservatively design them to withstand ground

FIGURE 6.16 Collapse of a freeway (a) Generalized geologic map of part of the San Francisco Bay, showing bay fill and mud and older alluvium. *(Modified after Hough, S. E., et al. 1990. Nature 344(6269):853–855. Copyright © Macmillan Magazines Ltd., 1990. Used by permission of the author)* (b) Collapsed freeway, as a result of the 1989 earthquake. *(Courtesy of Dennis Laduzinski)*



(a)

(b)

FIGURE 6.17 Earthquake damage Damage to buildings in the Marina district of San Francisco, resulting from the 1989 M 7.1 earthquake. *(John K. Nakata/USGS)*

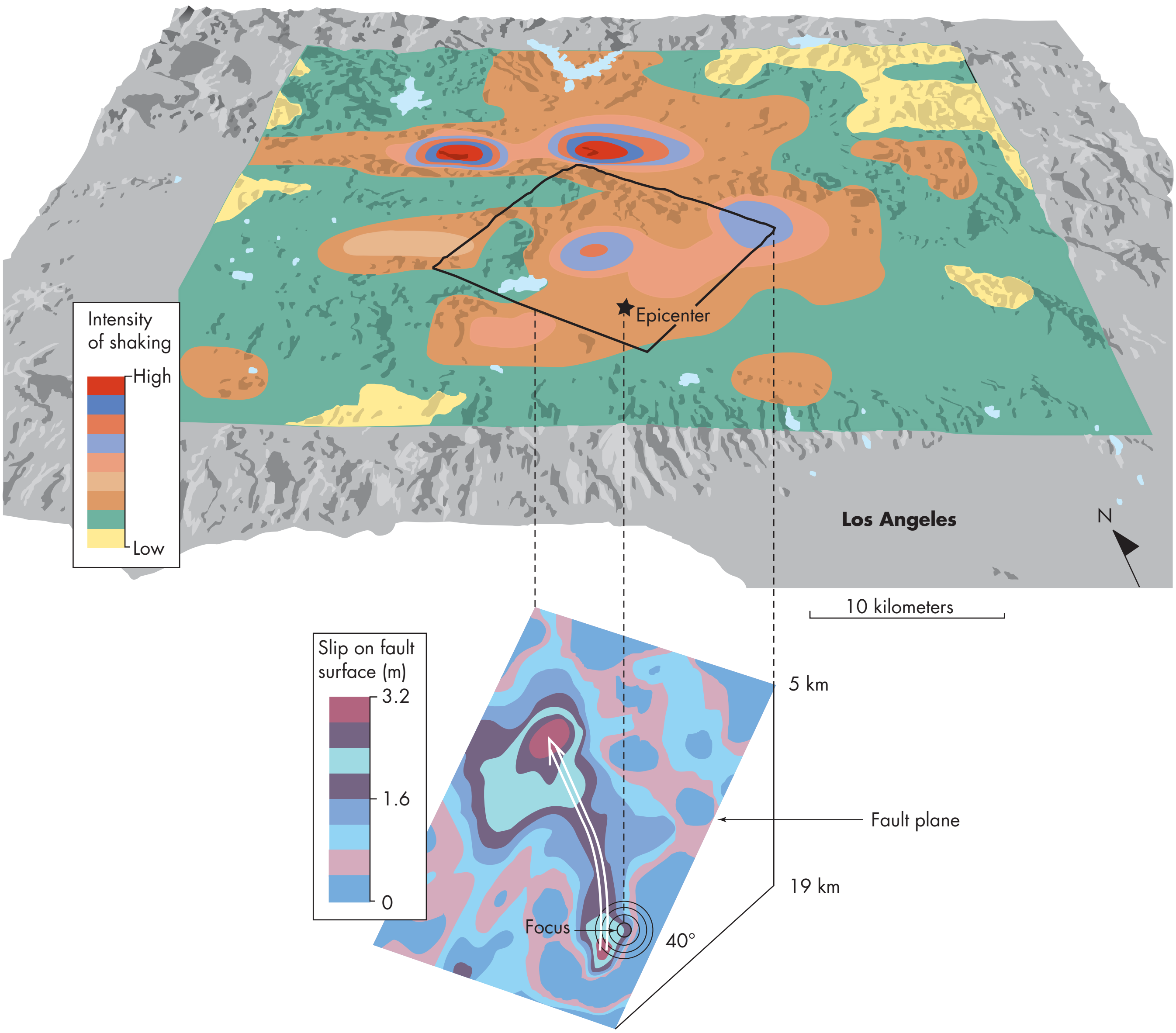


FIGURE 6.18 Epicenter and rupture path Aerial view of the Los Angeles region from the south, showing the epicenter of the M 6.7 1994 Northridge earthquake and showing peak ground motion in centimeters per second and the fault plane in its subsurface position. The path of the rupture is shown, along with the amount of slip in meters along the fault plane. The area that ruptured along the fault plane is approximately 430 km^2 (166 mi^2), and the fault plane is dipping at approximately 40 degrees to the south–southwest. Notice that the maximum slip and intensity of shaking both occur to the northwest of the epicenter. The fault rupture apparently began at the focus in the southeastern part of the fault plane and proceeded upward and to the northwest, as shown by the arrow. *(U.S. Geological Survey. 1996.* USGS Response to an Urban Earthquake, Northridge '94. *U.S. Geological Survey Open File Report 96–263)*

accelerations of about 0.6 to 0.7 *g*. To put this in perspective, consider that homes constructed of adobe, which are common in rural Mexico, South America, and the Middle East, can collapse under a horizontal acceleration of 0.1 *g*.[13] Unreinforced, prefabricated concrete buildings are also very vulnerable, at 0.2 to 0.3 *g*, as was tragically illustrated in the 1995 Sakhalin, Russia, earthquake (M 7.5). Two thousand of the 3,000 people in the town of Neftegorsk were killed when 17 prefabricated apartment buildings collapsed into rubble (**Figure 6.19**).

FIGURE 6.19 Buildings collapse in Russia Rows of prefabricated, unreinforced, five-story apartment buildings destroyed by the 1995 earthquake that struck the island of Sakhalin in Russia (M 7.5). *(Tanya Makeyeva/AP Photo)*

Supershear

Supershear occurs when the propagation of rupture is faster than the velocity of shear waves or surface waves produced by the rupture. The effect is analogous to supersonic aircraft breaking the sound barrier, producing a sonic boom. Supershear can produce shock waves that produce strong ground motion along the fault. The increased shear and shock may significantly increase the damage from a large earthquake. Supershear has been observed or suspected during several past earthquakes, including the 1906 San Francisco earthquake and the 2002 Denali earthquake in Alaska. Apparently, supershear is most likely to occur with strike-slip earthquakes that rupture a long straight fault segment of several tens to a hundred or more kilometers in length.

Depth of Focus

Recall that the point or area within Earth where an earthquake rupture starts is called the *focus* (see Figure 6.1). The *depth of focus* of an earthquake varies from just a few kilometers deep to almost 700 km (435 mi) below the surface. The deepest earthquakes occur along subduction zones, where slabs of oceanic lithosphere sink to great depths. The 2001 Seattle, Washington, earthquake (M 6.8) is an example of a relatively deep earthquake. Although the Seattle event was a large quake, about the same size as the 1994 Northridge earthquake, the focus was deeper, at about 52 km (32 mi) beneath Earth's surface. The focus was within the subducting Juan de Fuca plate (see Figures 2.6 and 2.10). Seismic waves had to move up 52 km (32 mi) before reaching the surface, and they lost much of their energy in the journey. As a result, the earthquake caused relatively little damage, considering its magnitude. In contrast, most earthquakes in southern California have focal depths of about 10 to 15 km (6 to 9 mi), although deeper earthquakes have occurred. These relatively shallow earthquakes are more destructive than deeper earthquakes of comparable magnitude because they are deep enough to generate strong seismic shaking, yet sufficiently close to the surface to cause strong surface shaking. A M 7.5 earthquake on strike-slip faults in the Mojave Desert near Landers, California, in 1992 had a focal depth of less than 10 km (6 mi). This event

(a)

(b)

FIGURE 6.20 Ground rupture from faulting (a) Cracking of the ground and damage to a building caused by the M 7.5 Landers earthquake, California. (b) Fence and dirt road offset to the right. *(Photos by Edward A. Keller)*

caused extensive ground rupture for about 85 km (53 mi).[16] Local vertical displacement exceeded 2 m (6.5 ft), and extensive lateral displacements of about 5 m (16 ft) were measured (Figure 6.20). If the Landers event had occurred in the Los Angeles Basin, extensive damage and loss of life would have occurred.

6.8 Earthquake Cycle

Observations of the 1906 San Francisco earthquake (M 7.7) led to a hypothesis known as the **earthquake cycle**. The earthquake cycle hypothesis proposes that there is a drop in elastic strain after an earthquake and there is a reaccumulation of strain before the next event.

Strain is deformation resulting from stress. *Elastic strain* may be thought of as deformation that is not permanent, provided that the stress is released. When the stress is released, the deformed material returns to its original shape. If the stress continues to increase, the deformed material eventually ruptures, making the deformation permanent. For example, consider a stretched rubber band or a bent archery bow; continued stress will snap the rubber band or break the bow. When a stretched rubber band or bow breaks, it experiences a rebound, in which the broken ends snap back, releasing their pent-up energy. A similar effect, referred to as *elastic rebound*, occurs after an earthquake (Figure 6.21). At time 1, rocks on either side of a fault segment have no strain built up and show no deformation. At time 2, elastic strain begins to build, caused by the tectonic forces that pull the rocks in opposite directions, referred to as shear stress. The rocks begin to bend. At time 3, elastic strain is accumulating, and the rocks have bent; however, they are still held together by friction. When the deformed rocks finally rupture, at time 4, the stress is released, and the elastic strain suddenly decreases as the sides of the fault "snap" into their new, or permanently deformed, position. After the earthquake, it takes time for sufficient elastic strain to accumulate again in order to produce another rupture.[17]

Stages of the Earthquake Cycle

It is speculated that a typical earthquake cycle has three or four stages. The first is a long period of seismic inactivity following a major earthquake and associated *aftershocks*, earthquakes that occur anywhere from a few minutes to a year or so after the main event. This is followed by a second stage, characterized by increased seismicity, as accumulated elastic strain approaches and locally exceeds the

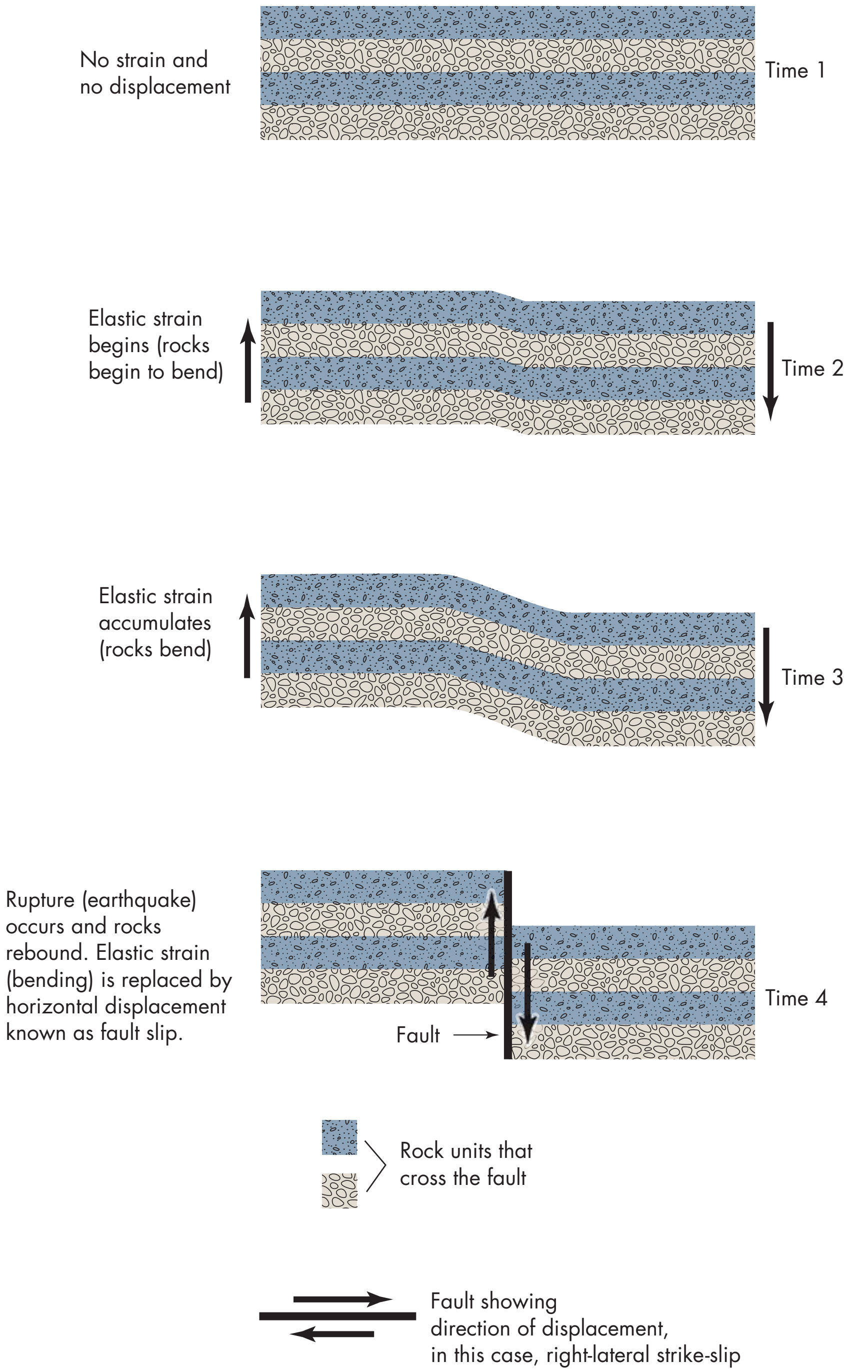


FIGURE 6.21 Earthquake cycle Idealized (map view) diagram illustrating the earthquake cycle. Moving from time 1 to time 4 may take from hundreds to thousands of years.

strength of the rock. The accumulated elastic strain initiates faulting that produces small earthquakes. The third stage of the cycle, which may occur only hours or days before the next large earthquake, consists of *foreshocks*. Foreshocks are small to moderate earthquakes that occur before the main event. For example, a M 6 earthquake may have foreshocks of about M 4. In some cases, this third stage may not occur. After the major earthquake, considered to be the fourth stage, the cycle starts over again.[17] Although the cycle is hypothetical and periods between major earthquakes are variable, the stages have been identified in the occurrence and reoccurrence of large earthquakes.

The Dilatancy-Diffusion Model

Although we have many empirical observations concerning physical changes in Earth materials before, during, and after earthquakes, no general agreement exists in terms of a physical model to explain the observations. One model, known as the **dilatancy-diffusion model**,[13,18] assumes that the first stage in earthquake development is an increase of elastic strain in rocks that causes them to **dilate** (undergo an inelastic increase in volume) after the stress on the rock reaches one-half the rock's breaking strength. During dilation, open fractures develop in the rocks, and it is at this stage that the first physical changes that might indicate a future earthquake take place.

Briefly, the model assumes that the dilatancy and fracturing of the rocks are first associated with a relatively low water pressure in the dilated rocks, which helps to produce lower seismic velocity (velocity of seismic waves through the rocks near a fault), more Earth movement, and fewer minor seismic events. An influx of water then enters the open fractures, causing the pore pressure to increase, which increases the seismic velocity and weakens the rocks. Radon gas dissolved in the water may also increase. The weakening facilitates movement along the fractures, which is recorded as an earthquake. After the movement and release of stress, the rocks resume many of their original characteristics.[18]

Considerable controversy surrounds the validity of the dilatancy-diffusion model. One aspect of the model gaining considerable favor is the role of **fluid pressure** (force per unit area exerted by a fluid) in earthquakes. As we learn more about rocks at seismogenic (earthquake generating) depths, it is apparent that much water is present. Deformation of the rocks and a variety of other processes are thought to increase the fluid pressure at depth, and this results in a lowering of the strength of the rocks. If the fluid pressure becomes sufficiently high, this can facilitate the occurrence of earthquakes. Empirical data from several environments, including subduction zones and active fold belts, suggest that high fluid pressures are present in many areas where earthquakes occur. Thus, there is increasing interest in the role of fluid flow in fault displacement and the earthquake cycle. The **fault-valve mechanism**[19] hypothesizes that fluid (usually water) pressure rises until failure occurs, thus triggering an earthquake, along with upward fluid discharge. This may explain why, following some earthquakes, springs discharge more water and dry streams may start flowing (i.e., groundwater seeps into channels). Increased flow (i.e., discharge) of groundwater may occur for months following a large earthquake.

6.9 Earthquakes Caused by Human Activity

Several human activities are known to increase or cause earthquake activity. Damage from human-caused earthquakes is regrettable, but the lessons learned may help to control or stop large catastrophic earthquakes in the future. Three ways that the actions of people have caused earthquakes are:

- Loading the Earth's crust, as in building a dam and reservoir
- Disposing of waste deep into the ground through disposal wells
- Setting off underground nuclear explosions

Reservoir-Induced Seismicity

During the 10 years following the completion of Hoover Dam on the Colorado River in Arizona and Nevada, several hundred local tremors occurred. Most of them were very small, but one was M 5 and two were about M 4.[17] An earthquake in India, approximately M 6, killed about 200 people after the construction and filling of a reservoir. Evidently, fracture zones may be activated both by the increased load of water on the land and by the increased water pressure in the rocks below the reservoir, resulting in faulting.

Deep Waste Disposal

From April 1962 to November 1965, several hundred earthquakes occurred in the Denver, Colorado, area. The largest earthquake was M 4.3 and caused sufficient shaking to knock bottles off shelves in stores. The source of the earthquakes was eventually traced to the Rocky Mountain Arsenal, which was manufacturing materials for chemical warfare. Liquid waste from the manufacturing process was being pumped down a deep disposal well to a depth of about 3,600 m (11,800 ft). The rock receiving the

waste was highly fractured metamorphic rock, and injection of the new liquid facilitated slippage along fractures. Study of the earthquake activity revealed a high correlation between the rate of waste injection and the occurrence of earthquakes. When the injection of waste stopped, so did the earthquakes (Figure 6.22).[20] Fluid injection of waste as an earthquake trigger was an important occurrence because it directed attention to the fact that earthquakes and fluid pressure are related.

Nuclear Explosions

Numerous earthquakes with magnitudes as large as 5.0 to 6.3 have been triggered by underground nuclear explosions at the Nevada Test Site. Analysis of the aftershocks suggests that the explosions caused some release of natural tectonic strain. This led to discussions by scientists about whether nuclear explosions might be used to prevent large earthquakes by releasing strain before it reaches a critical point.

6.10 Effects of Earthquakes

Shaking is not the only cause of death and damage in earthquakes: Catastrophic earthquakes have a wide variety of destructive effects. Primary effects—those caused directly by fault movement—include

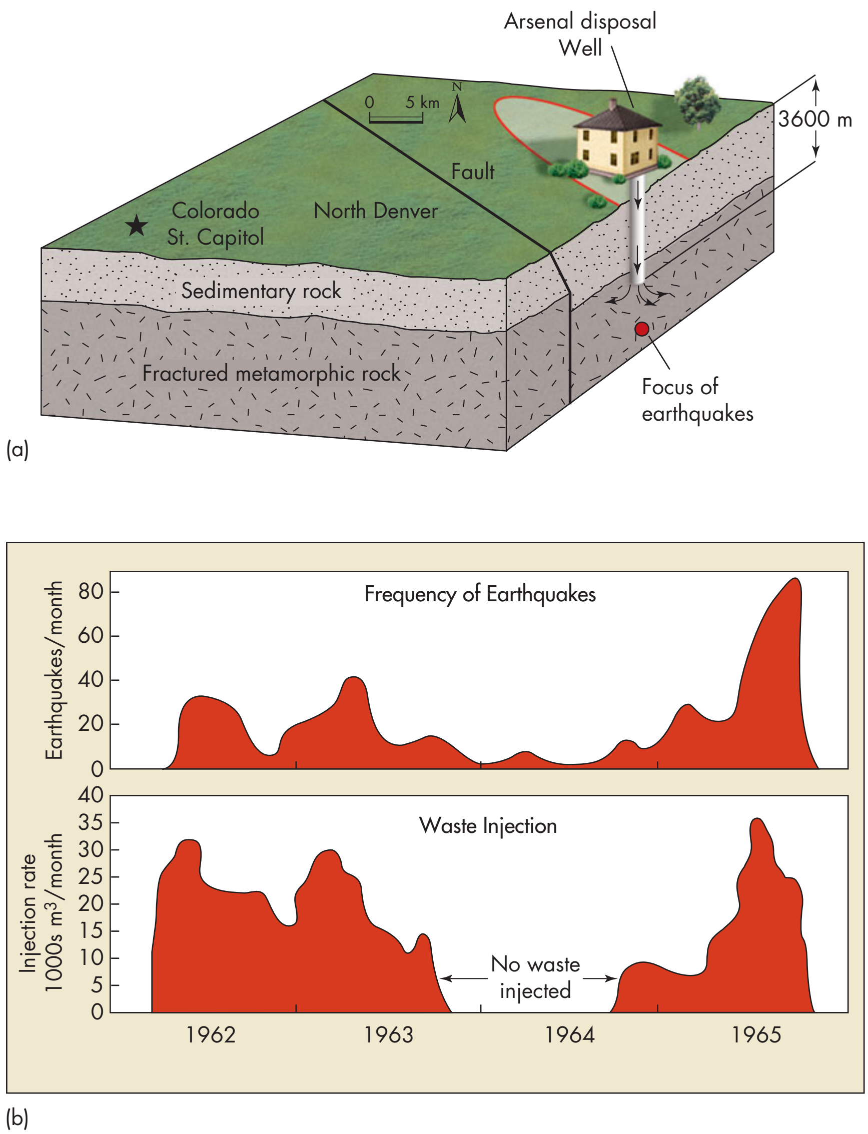


FIGURE 6.22 Human-caused earthquakes (a) Generalized block diagram showing the Rocky Mountain Arsenal well. The red line encompasses an area where most of the earthquakes occurred and a natural fault is present about 10 km southwest of the disposal well. (b) Graph showing the relationship between earthquake frequency and the rate of injection of liquid waste. Injection of waste stoppen in 1966 and the well was permanently sealed in 1986. Earthquake activity has settled back to the natural frequency. An earthquake magnitude of 4.1 occurred in 1982, suggesting the faulting remains active *(Data from www.geosurvey.state.co.us. Rocky Mountain Arsenal--The most famous example of induced earthquakes. Accessed 12/5/10)*

ground shaking and its effects on people and structures and surface rupture. Secondary effects induced by the faulting and shaking include liquefaction of the ground, landslides, fires, disease, tsunami, and regional changes in ground and surface water, as well as land elevation.

Shaking and Ground Rupture

The immediate effects of a catastrophic earthquake can include violent ground shaking, accompanied by widespread surface rupture and displacements. Surface rupture with a vertical component produces a *fault scarp*. A fault scarp is a linear, steep slope that looks something like a curb on a street. Fault scarps are often approximately 1 m (3.3 ft) or more high and extend for a variable distance, from a few tens of meters to a few kilometers along a fault (**Figure 6.23**). The 1906 San Francisco earthquake (M 7.7) produced 6.5 m (21.3 ft) of horizontal displacement, or fault-slip, along the San Andreas fault north of San Francisco and reached a maximum Modified Mercalli Intensity of XI.[13] At this intensity, surface accelerations can snap and uproot large trees and knock people to the ground. The shaking may damage or collapse large buildings, bridges, dams, tunnels, pipelines, and other rigid structures. The great 1964 Alaskan earthquake (M 8.3) caused extensive damage to transportation systems, railroads, airports, and buildings. The 1989 Loma Prieta earthquake (M 7.1) was much smaller than the Alaska event, yet it caused about $5 billion of damage. The 1994 Northridge earthquake (M 6.7) caused 57 deaths and inflicted about $40 billion in damage, making it one of the most expensive hazardous events ever in the United States. *The Northridge earthquake caused so much damage because there was so much there to be damaged*. The Los Angeles region is highly urbanized, with a high population density, and the seismic shaking was intense.

Liquefaction

Liquefaction is the transformation of water-saturated granular material, or sediments, from a solid to a liquid state. During earthquakes, liquefaction may result from compaction of sediments during intense shaking. Liquefaction of near-surface water-saturated silts and sand causes the materials to lose their strength and to flow. As a result, buildings may tilt or sink into the liquefied sediments, while tanks or pipelines buried in the ground may rise buoyantly.[21]

Landslides

Earthquake shaking often triggers landslides, a comprehensive term for several types of hill slope failure, in hilly and mountainous areas. Landslides can be extremely destructive and can cause great loss of life, as demonstrated by the 1970 Peru earthquake. In that event, more than 70,000 people died, and, of those, 20,000 were killed by a giant landslide that buried the cities of Yungan and Ranrahirca. Both the 1964 Alaskan earthquake and the 1989 Loma Prieta

FIGURE 6.23 Fault scarp Fault scarp produced by the 1992 M 7.5 Landers earthquake in California. *(Edward A. Keller)*

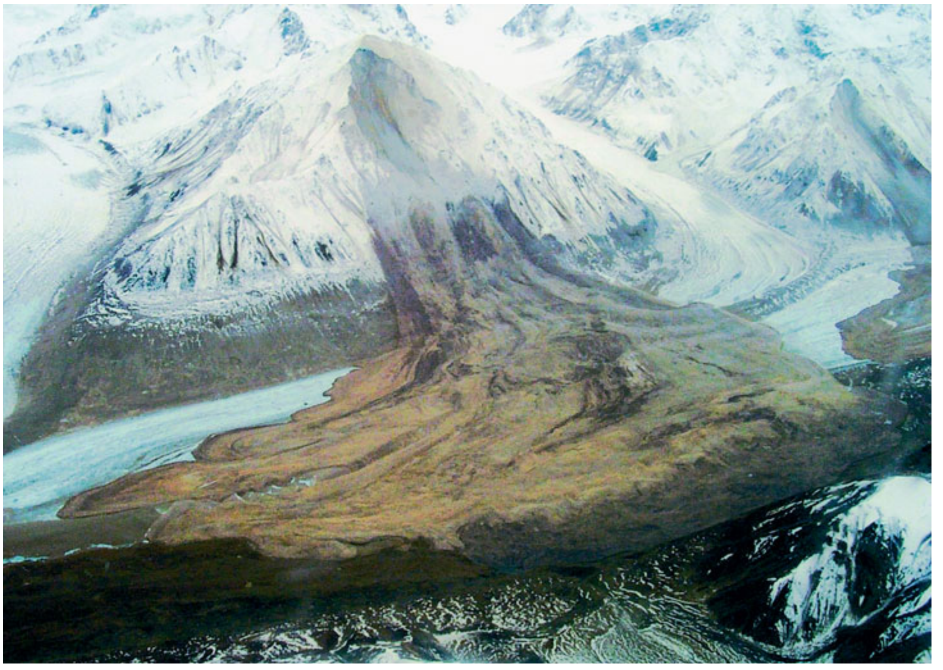


FIGURE 6.24 Earthquake-triggered landslides This giant landslide was one of thousands triggered by the 2002 (M 7.9) Alaskan earthquake. Landslide deposits cover part of the Black Rapids Glacier. *(USGS)*

FIGURE 6.25 Landslide in El Salvador The brown area in the center of this image is the landslide that buried more than 500 homes in the Las Colinas neighborhood of Santa Tecla, a western suburb of San Salvador, the capital of El Salvador. The landslide, which killed more than 500 people, was triggered by a January 2001 earthquake. *(USGS)*

earthquake caused extensive landslide damage to buildings, roads, and other structures. The 1994 Northridge earthquake and aftershocks triggered thousands of landslides. A giant landslide from the side of a mountain was triggered by the 2002 Alaska earthquake (**Figure 6.24**). Thousands of other landslides were also triggered by the earthquake, most of which were on the steep slopes of the Alaska Range.

A large landslide associated with the January 13, 2001, El Salvador earthquake (M 7.6) buried the community of Las Colinas, killing hundreds of people (**Figure 6.25**). Tragically, the landslide could probably have been avoided if the slope that failed had not previously been cleared of vegetation for the construction of luxury homes.

The 2008 M 7.9 earthquake in China caused many landslides. Very large landslides (**Figure 6.26**) buried villages and blocked rivers, forming "earthquake lakes" that produced a serious flood hazard, should the landslide dam fail by overtopping or erosion. Channels were excavated to slowly drain lakes and reduce the flood hazard.[22]

Fires

Fire is a major hazard associated with earthquakes. Shaking of the ground and surface displacements can break electrical power and gas lines, thus starting fires. In individual homes and other buildings, appliances such as gas heaters may be knocked over, causing gas leaks that could be ignited. The threat from fire is intensified because firefighting equipment may

FIGURE 6.26 M 7.9 earthquake in China A 2008 earthquake produced a huge landslide that blocked a river, producing an "earthquake lake." Channels in the landslide dam were excavated to lower the lake level and reduce a potential flood hazard by overtopping or erosion. *(AP Photo)*

FIGURE 6.27 Earthquake and fire Fires associated with the 1995 Kobe, Japan, earthquake caused extensive damage to the city. *(Corbis)*

become damaged, and essential water mains may be broken during an earthquake. Earthquakes in both Japan and the United States have been accompanied by devastating fires (**Figure 6.27**). The San Francisco earthquake of 1906 has been repeatedly referred to as the "San Francisco Fire," and, in fact, 80 percent of the damage from that event was caused by firestorms that ravaged the city for several days. The 1989 Loma Prieta earthquake also caused large fires in the Marina district of San Francisco.

Disease

Landslides from the 1994 Northridge earthquake raised large volumes of dust, some of which contained fungi spores that cause valley fever. Winds carried the dust and spores to urban areas, including Simi Valley, where an outbreak of valley fever occurred during an 8-week period after the earthquake. Two hundred cases were diagnosed, which is 16 times the normal infection rate; of these, 50 people were hospitalized and 3 died.[11] Earthquakes can rupture sewer and water lines, causing water to become polluted by disease-causing organisms. The death of animals and people buried in earthquake debris also produces potential sanitation problems that may result in an outbreak of disease.

Regional Changes in Groundwater and Land Elevation

Earthquakes can alter groundwater levels and stream flow. Earth materials, such as fine sediment (i.e., sand, silt) when shaken can consolidate, forcing water out (i.e., initiating spring or stream flow). Earthquakes can also fracture rock, increasing pore spaces or cleaning out fractures to increase groundwater flow. Changes in water level and stream flow tend to increase with earthquake magnitude. Groundwater change from a large earthquake can occur hundreds to thousands of kilometers from the epicenter, while changes in stream flow (usually increases) can occur tens to hundreds of kilometers from the epicenter.[23,24]

Vertical deformation, including both uplift and subsidence, is another effect of some large earthquakes. Such deformation can cause regional changes in groundwater levels. The great 1964 Alaskan earthquake (M 8.3) caused regional uplift and subsidence.[25] The uplift, which was as much as 10 m (33 ft), and the subsidence, which was as much as 2.4 m (7.8 ft), caused effects ranging from severely disturbing or killing coastal marine life to changes in groundwater levels. In areas of uplift, canneries and fishermen's homes were displaced above the high-tide line, rendering docks and other facilities inoperable. The subsidence resulted in flooding of some communities. In 1992, a major earthquake (M 7.1) near Cape Mendocino in northwestern California produced approximately 1 m (3.3 ft) of uplift at the shoreline, resulting in the death of marine organisms exposed by the uplift.[26]

Tsunami

Tsunami (from the Japanese word for "large harbor waves") are produced by the sudden vertical displacement of ocean water. Tsunami (the subject of Chapter 7) are a serious natural hazard that can cause catastrophes thousands of kilometers from where they originate.

6.11 Earthquake Risk and Earthquake Prediction

The great damage and loss of life associated with earthquakes are due, in part, to the fact that they often strike without warning. A great deal of research is being devoted to anticipating earthquakes. The best we can do at present is to use probabilistic methods to determine the risk associated with a particular area or with a particular segment of a fault. Such determinations of risk are a form of long-term prediction: We can say that an earthquake of a given magnitude or intensity has a high probability of occurring in a given area or fault segment within a specified number of years. These predictions assist planners who are considering seismic safety measures or people who are deciding where to live. However, long-term prediction does not help residents of a seismically active area to anticipate and prepare for a specific earthquake over a period of days or weeks before an event. Short-term prediction, specifying the time and place of the earthquake, would be much more useful, but the ability to make such predictions has eluded us. Predicting imminent earthquakes depends to a large extent on observation of precursory phenomena, or changes preceding the event.

Estimation of Seismic Risk

The earthquake risk associated with a particular area is shown on seismic hazard maps, which are prepared by scientists. Some of these maps show relative hazard—that is, where earthquakes of a specified magnitude have occurred. However, a preferable method of assessing seismic risk is to calculate the probability of either a particular event or the amount of shaking likely to occur. **Figure 6.28a** shows an earthquake hazard map for the United States. It was prepared on the basis of the probability of horizontal ground motion. The darkest areas on the map represent the regions of greatest seismic hazard because those areas

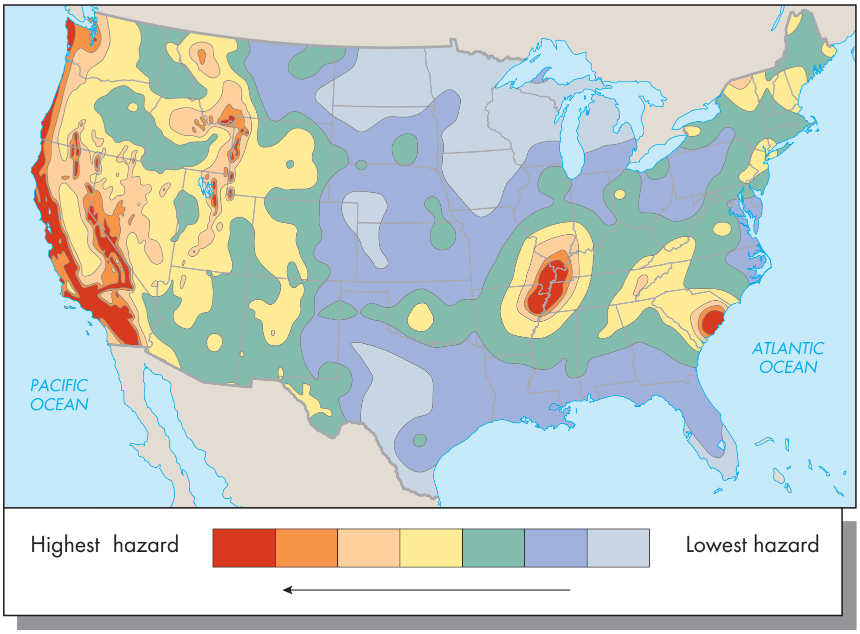


FIGURE 6.28a Earthquake hazard map A probabilistic approach to the seismic hazard in the United States. Colors indicate level of hazard. *(From U.S. Geological Survey Fact Sheet 2008–3027)*

have the highest probability of experiencing the greatest seismic shaking. Regional earthquake hazard maps are valuable; however, considerably more data are necessary to evaluate hazardous areas in order to assist in the development of building codes and the determination of insurance rates. **Figure 6.28b** shows that the probability of one or more M 6.7 or larger earthquakes occurring over a 30 year period in California is a near certainty. The probability for a M 7.5 is also high; for M 8, the probability is about 1 in 25.[27,28] Four sources of data were used to estimate the probability of earthquakes:[27]

- *Geology:* the mapped location of faults with documented offsets
- *Paleoseismology:* the study of past earthquake history from trenches excavated across faults to determine dates and amount of displacement from past events
- *Geodesy:* the determination, most often from global positioning systems (GPSs), of how fast Earth's tectonic plates are moving
- *Seismology:* the occurrence of past earthquakes detected by seismographs located at many locations that monitor when earthquakes occur and how strong they are

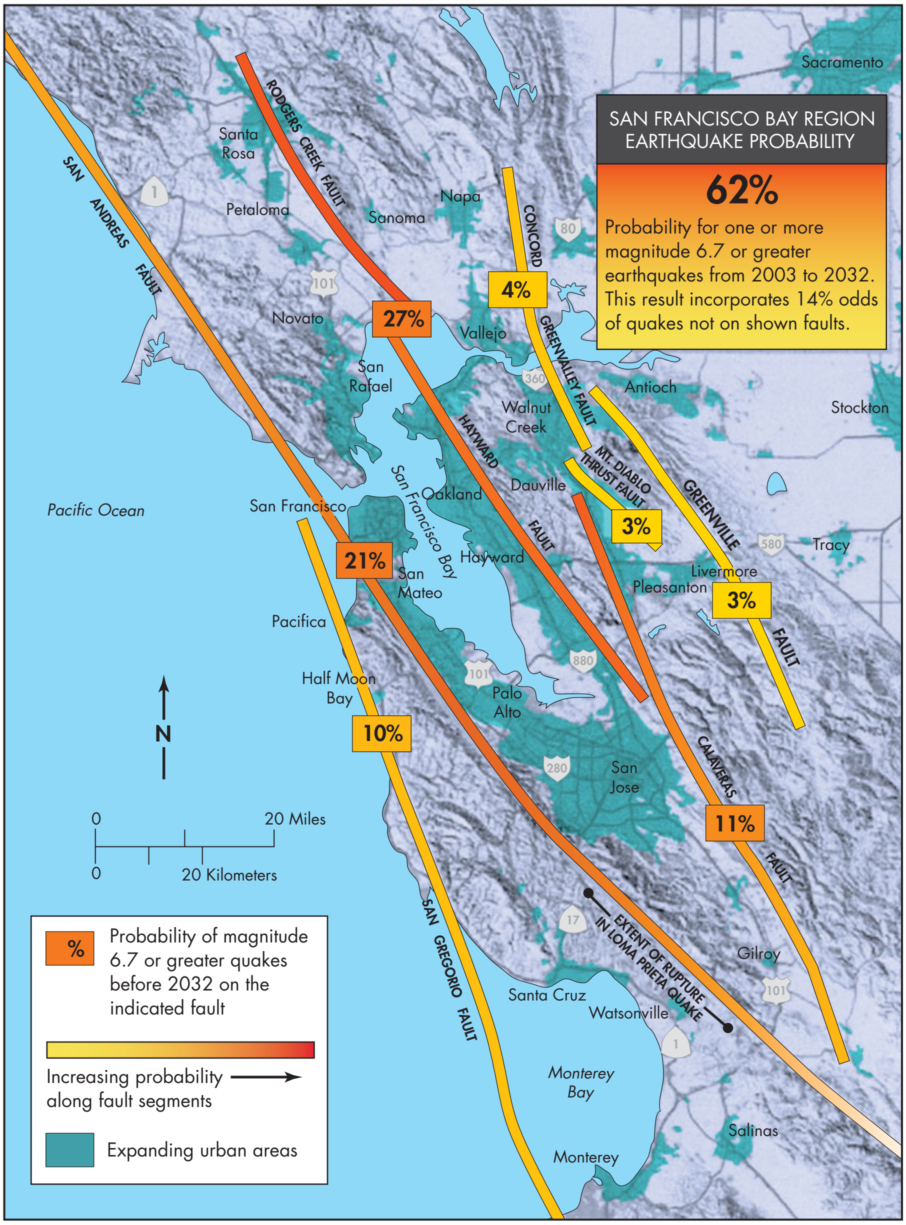
Short-Term Prediction

The short-term prediction, or *forecast*, of earthquakes is an active area of research. Similarly to a weather forecast, an earthquake forecast specifies a relatively short time period in which the event is likely to occur and assigns it a probability of occurring. The basic procedure for predicting earthquakes was once thought to be as easy as "one-two-three."[29] First, deploy instruments to detect potential precursors of a future earthquake; second, detect and recognize the precursors in terms of when an earthquake will occur and how big it will be; and, third, after review of your data, publicly predict the earthquake. Unfortunately, earthquake prediction is much more complex than first thought.[29]

The Japanese made the first attempts at earthquake prediction with some success, based on the frequency of microearthquakes (M less than 2), repetitive surveys of land levels, and a change in the local magnetic field of Earth. They found that earthquakes in the areas they studied were nearly always accompanied by swarms of microearthquakes that occurred several months before the major shocks. Furthermore, ground tilt was correlated strongly with earthquake activity.

Chinese scientists made the first successful prediction of a major earthquake in 1975. The February 4, 1975, Haicheng earthquake (M 7.3) destroyed or damaged about 90 percent of buildings in the city, which had a population of 9,000. The short-term prediction was based primarily on a series of foreshocks that began 4 days before the main event. On February 1 and 2, several shocks with a magnitude of less than 1 occurred. On February 3, less

FIGURE 6.28b Probabilities of earthquakes in California Probability of at least one M 6.7 or greater earthquake occurring over the next 30 year period (2003–2032) on a particular fault. *(Field, E. H., Milner, K. R., and the 2007 Working Group on California Earthquake Probabilities. 2008.* Forecasting California's Earthquakes—What Can We Expect in the Next 30 Years? *U.S. Geological Survey Fact Sheet 2008–3027)*



than 24 hours before the main shock, a foreshock of M 2.4 occurred, and, in the next 17 hours, eight shocks with a magnitude greater than 3 occurred. Then, as suddenly as it began, the foreshock activity became relatively quiet for 6 hours, until the main earthquake occurred.[30] Haicheng's population of 9,000 was saved by a massive evacuation from potentially unsafe housing just before the earthquake.

Unfortunately, foreshocks do not always precede large earthquakes. In 1976, one of the deadliest earthquakes in recorded history struck near the mining town of Tanshan, China, killing several hundred thousand people. There were no foreshocks. Earthquake prediction is still a complex problem, and it will probably be many years before dependable short-range prediction is possible. Such predictions most likely will be based upon precursory phenomena such as:

- Patterns and frequency of earthquakes, such as the foreshocks used in the Haicheng prediction
- Preseismic deformation of the ground surface
- Emission of radon gas
- Seismic gaps along faults
- Anomalous animal behavior (?)

Preseismic Deformation of the Ground Surface

Rates of uplift and subsidence, especially when they are rapid or anomalous, may be significant in predicting earthquakes. For more than 10 years before the 1964 earthquake near Niigata, Japan (M 7.5), there was a broad uplift of Earth's crust of several centimeters near the Sea of Japan coast. Similarly, broad slow uplift of several centimeters occurred over a 5 year period before the 1983 Sea of Japan earthquake (M 7.7).[18]

Preinstrument uplifts of 1 to 2 m (3.3 to 6.6 ft) preceded large Japanese earthquakes in 1793, 1802, 1872, and 1927. Although these uplifts are not well understood, they could have been indicators of the impending earthquakes. These uplifts were recognized by sudden withdrawals of the sea from the land, often as much as several hundred meters in harbors. For example, on the morning of the 1802 earthquake, the sea suddenly withdrew about 300 m (984 ft) from a harbor in response to a preseismic uplift of about 1 m (3.3 ft). Four hours later, the earthquake struck, destroying many houses and uplifting the land another meter, causing the sea to withdraw an even greater distance.[31]

Emission of Radon Gas

The levels of radon, a radioactive gas, have been observed to increase significantly before some earthquakes. It is believed that, before an earthquake, rocks expand, fracture, and experience an influx of water. Radon gas, which is naturally present in rocks, moves with the water. There was a significant increase in radon gas measured in water wells a month or so before the 1995 Kobe, Japan, earthquake (M 7.2).[32]

Seismic Gaps

Seismic gaps are defined as areas along active fault zones or within regions that are likely to produce large earthquakes but have not caused one recently. The lack of earthquakes is interpreted to be temporary; furthermore, these areas are thought to store tectonic strain and are, thus, candidates for future large earthquakes.[33] Seismic gaps have been useful in medium-range earthquake prediction. At least 10 large plate boundary earthquakes have been successfully forecast from seismic gaps since 1965, including one in Alaska, three in Mexico, one in South America, three in Japan, and one in Indonesia. In the United States, seismic gaps along the San Andreas fault include one near Fort Tejon, California, that last ruptured in 1857 and one along the Coachella Valley, a segment that has not produced a great earthquake for several hundred years. Both gaps are likely candidates to produce a great earthquake in the next few decades.[17,33]

As Earth scientists examine patterns of seismicity, two ideas are emerging. First, there are sometimes reductions in small or moderate earthquakes prior to a larger event. For example, prior to the 1978 (M 7.8) Oaxaca, Mexico, earthquake, there was a 10-year period (1963 to 1973) of relatively high seismicity of earthquakes (mostly M 3 to 6.5), followed by a quiescence period of 5 years. Renewed activity beginning 10 months before the M 7.8 event was the basis of a successful prediction.[31] Second, small earthquakes may tend to ring an area where a larger event might eventually occur. Such a ring (or donut) was noticed in the 16 months prior to the 1983 M 6.2 event in Coalinga, California. Unfortunately, hindsight is clearer than foresight, and this ring was not noticed or identified until after the event.

Anomalous Animal Behavior (?)

Anomalous animal behavior has often been reported before large earthquakes. Reports have included dogs barking unusually, chickens refusing to lay eggs, horses or cattle running in circles, rats perching on power lines, and snakes crawling out in the winter and freezing. Anomalous behavior of animals was evidently common before the Haicheng earthquake.[30] Years ago, it was suggested that, sometime in the future, we might have animals, such as ground squirrels or snakes in cages, along faults, and that somehow they would tell us when an earthquake is likely to occur in the near future. Undoubtedly, some animals are much more sensitive to Earth movements and possible changes in Earth before an earthquake or landslide than are people. However, the significance and reliability of animal behavior are very difficult to evaluate. There is little research going on to further explore anomalous animal behavior in the United States, but it remains one of the interesting mysteries surrounding earthquakes.

6.12 Toward Earthquake Prediction

We are still a long way from a working, practical methodology with which to reliably predict earthquakes. However, a good deal of information is currently being gathered concerning possible precursor phenomena associated with earthquakes. To date, the most useful precursor phenomena have been patterns of earthquakes, particularly foreshocks, and seismic gaps. Optimistic scientists around the world today believe that we will eventually be able to make consistent long-range forecasts (tens to a few thousand years), medium-range predictions (a few years to a few months), and short-range predictions (a few days or hours) for the general locations and magnitudes of large, damaging earthquakes.

Although progress on short-range (days to months) earthquake prediction has not matched expectations, medium- to long-range forecast (years to decades), based on the probability of an earthquake occurring on a particular fault, has progressed faster than expected. The October 28, 1983, Borah Peak earthquake in central Idaho (M 7.3) has been lauded as a success story for medium-range earthquake hazard evaluation. Previous evaluation of the Lost River fault suggested that the fault was active.[34] The earthquake killed two people and caused approximately \$15 million in damages. Fault scarps up to several meters high and numerous ground fractures along the 36 km (22 mi) rupture zone of the fault were produced as a result of the earthquake. The important fact was that the scarp and faults produced during the earthquake were superimposed on previously existing fault scarps, validating the usefulness of careful mapping of scarps produced from prehistoric earthquakes. Remember: Where the ground has broken before, it is likely to break again!

6.13 Sequence of Earthquakes in Turkey: Can One Earthquake Set up Another?

There is considerable controversy regarding patterns of repetitive earthquakes. Do earthquakes on a given fault have return periods that are relatively constant with relatively constant-magnitude earthquakes, or do they tend to occur in clusters over a period of several hundred to several thousand years? Undoubtedly, one of the most remarkable sites in the world for paleoseismic studies is Pallett Creek, located approximately 55 km northeast of Los Angeles on the Mojave segment of the San Andreas fault. The site contains evidence of 10 large earthquakes, 2 of which occurred in historical time (1812 and 1857), and prehistoric events extending back to approximately A.D. 671.[35] High-precision radiocarbon dating methods provide accurate dating of most of the 8 prehistoric events. When the dates and their accompanying error bars are plotted, it is apparent that the earthquakes are not evenly distributed through time but tend to cluster. Most of the earthquakes within clusters are separated by a few decades, but the time between clusters varies from approximately 160 to 360 years. The earthquakes were identified through careful evaluation of natural exposures and fault trenches at Pallett Creek.[35] **Figure 6.29** shows part of the trench wall and the offset of organic-rich sedimentary layers that correspond to an earthquake that occurred in approximately A.D. 1100. Naturally, the question we wish to ask is, when will the next big earthquake occur on the Mojave segment of the San Andreas fault? Studies using conditional probability suggest that probability is approximately 60 percent for the next 30-year period (see Figure 6.28b). Assuming that the two historic events are a cluster and, if clusters can be separated by approximately 160 to 360 years, then the next large earthquake might be expected between the years 2017 and 2207. On the other hand, the data set at Pallett Creek, although the most complete record for any fault in the world, is still a study of small numbers.

A study of the San Andreas fault, about 200 km (125 mi) northwest of Pallett Creek, discovered evidence for six earthquakes since A.D. 1360, with average return period of about a century (88±41 years). The size distribution of these events is not well constrained. Some could be strong earthquakes (M 6.5 to 7), while others could be major earthquakes (M 7.5 to 7.9).[36] The more we learn about the San Andreas fault, the more variable past earthquakes seem to be in terms of both time and magnitude. However, major events appear to occur about every 150 years on average, which is about the time since the last big one in 1857.

Some faults, evidently, do produce earthquakes of similar magnitude over relatively constant return periods. However, as we learn more about individual

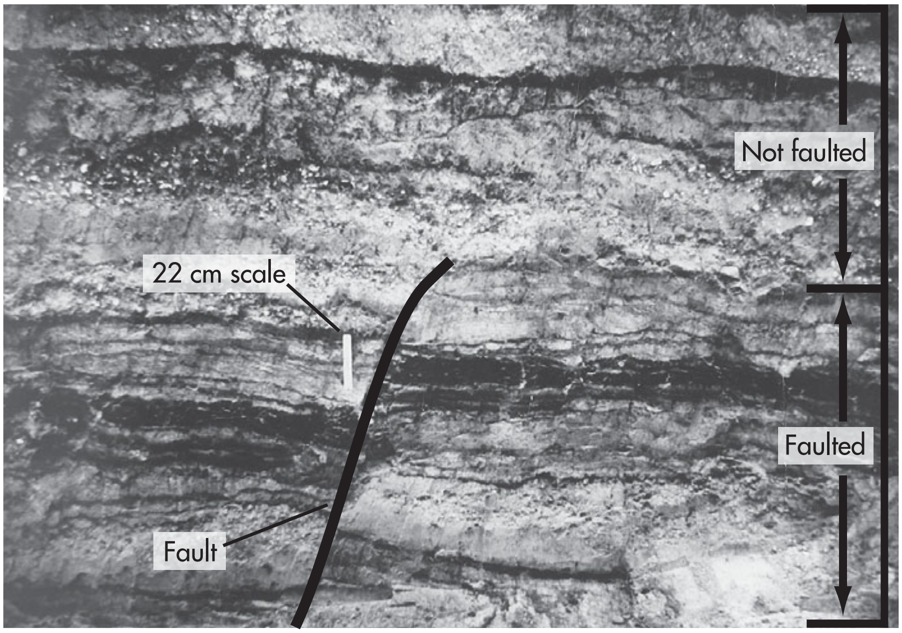


FIGURE 6.29 Pallett Creek Part of the trench wall crossing the San Andreas fault at Pallett Creek, showing a 30 cm offset. Notice that the strata above the 22 cm scale (central part of photograph) are not offset. The offset sedimentary layers (white bed) and the dark organic layers were produced by an earthquake that occurred about 800 years ago. *(Courtesy of Kerry Sieh)*

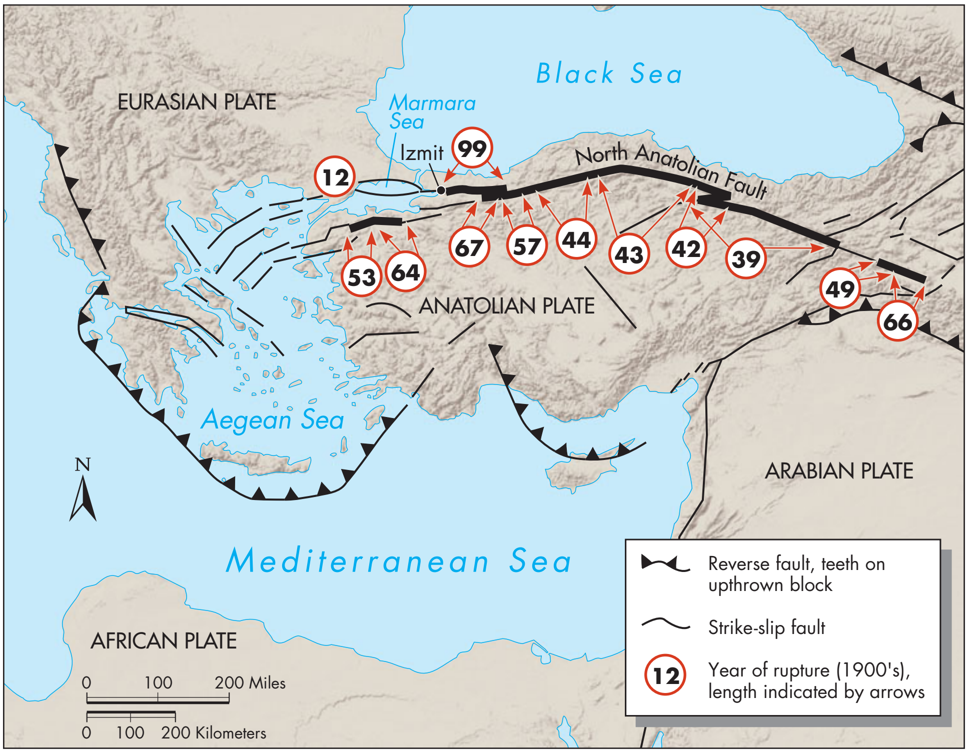


FIGURE 6.30 Sequence of earthquakes Earthquakes (M greater than 6.7) on the North Anatolian fault in the twentieth century. Events of 1992 and 1951 are not shown. Year 1999 shows the rupture length of two events combined (Izmit, August; and Duzce, November). *(Modified after Reilinger, R., Toksot, N., McClusky, S., and Barka, A. 2000. 1999 Izmit, Turkey earthquake was no surprise.* GSA Today *10(1):1–5)*

faults, we learn that there is a great deal of variability concerning magnitudes of earthquakes and their return periods for a given fault system. For example, in the twentieth century, a remarkable series of earthquakes with magnitude greater than 6.7 generally occurred from east to west on the North Anatolian fault in Turkey, resulting in surface ruptures along a 1,000 km (621 mi) section of the fault (Figure 6.30). Two events in 1999—the Izmit (M 7.4) and the Duzce (M 7.1) earthquakes—were particularly severe, causing billions of dollars in property damage and thousands of deaths. The sequence of earthquakes

has been described as a "falling-domino scenario," in which one earthquake sets up the next, eventually rupturing nearly the entire length of the fault, in a cluster of events.[37,38] Clusters of earthquakes that form a progressive sequence of events in a relatively short period of time are apparently separated by a period of no earthquakes for several hundred years. A similar sequence or clustering may be occurring along the fault bordering the Sumatra Plate boundary in Indonesia. Three earlier large earthquakes from 1600 to 1833, discovered from the geologic record, preceded the 2004 event, and a M 8.7 event occurred in 2005. That earthquake did not produce a tsunami, but it collapsed buildings and took about 1,000 lives.[7] Understanding processes related to clustering of earthquakes along a particular fault is very important if we are to plan for future seismic events in a given region. The fact that there may not have been a large damaging earthquake for several hundred years may not be as reassuring as we once thought.

6.14 The Response to Earthquake Hazards

Responses to seismic hazards in earthquake-prone areas include development of hazard-reduction programs, careful siting of critical facilities, engineering and land-use adjustments to earthquake activity, and development of a warning system. The extent to which these responses occur depends, in part, on people's perception of the hazard.

Earthquake Hazard-Reduction Programs

In the United States, the U.S. Geological Survey (USGS), as well as university and other scientists, are developing the National Earthquake Hazard Reduction Program. The major goals of the program are to:

- **Develop an understanding of the earthquake source:** This requires an understanding of the physical properties and mechanical behavior of faults, as well as development of quantitative models of the physics of the earthquake process.
- **Determine earthquake potential:** This determination involves characterizing seismically active regions, including determining the rates of crustal deformation; identifying active faults; determining characteristics of paleoseismicity; estimating strong ground motion, slip rate, and earthquake recurrence interval; calculating long-term probabilistic forecasts; and developing methods of intermediate- and short-term prediction of earthquakes. (See A Closer Look: Earthquake Hazard Evaluation: Ground Motion and Slip Rate.)
- **Predict effects of earthquakes:** Predicting effects includes gathering the data necessary for predicting ground rupture and shaking and for predicting the response of structures that we build in earthquake-prone areas and evaluating the losses associated with the earthquake hazard. (See A Closer Look: The Alaska Earthquake of 2002 and the Value of Estimating Potential Ground Rupture.)
- **Apply research results:** The program is interested in transferring knowledge about earthquake hazards to people, communities, states, and the nation. This knowledge concerns what can be done to better plan for earthquakes and to reduce potential losses of life and property.

Adjustments to Earthquake Activity

The mechanism of earthquakes is still poorly understood; therefore, such adjustments as warning systems and earthquake prevention are not yet reliable alternatives. There are, however, reliable protective measures we can take:

- *Structural protection*, including the construction of large buildings and other structures, such as dams, power plants, and pipelines able to accommodate moderate shaking or surface rupture. This measure has been relatively successful in the United States. (See A Closer Look: The Alaska Earthquake of 2002 and the Value of Estimating Potential Ground Rupture.) The 1988 Armenia earthquake (M 6.8) was somewhat larger than the 1994 Northridge event (M 6.7), but the loss of life and destruction in Armenia were staggering. At least 45,000 people were killed, compared with 57 in California, and near-total destruction occurred in some towns near the epicenter. Most buildings in Armenia were constructed of unreinforced concrete and instantly crumbled into rubble, crushing or trapping their occupants. The 2005 Pakistan M 7.6 earthquake killed more than 80,000 people. Many of the deaths occurred as apartment buildings with little or no steel reinforcement collapsed to resemble a

A Closer Look

Earthquake Hazard Evaluation: Ground Motion and Slip Rate

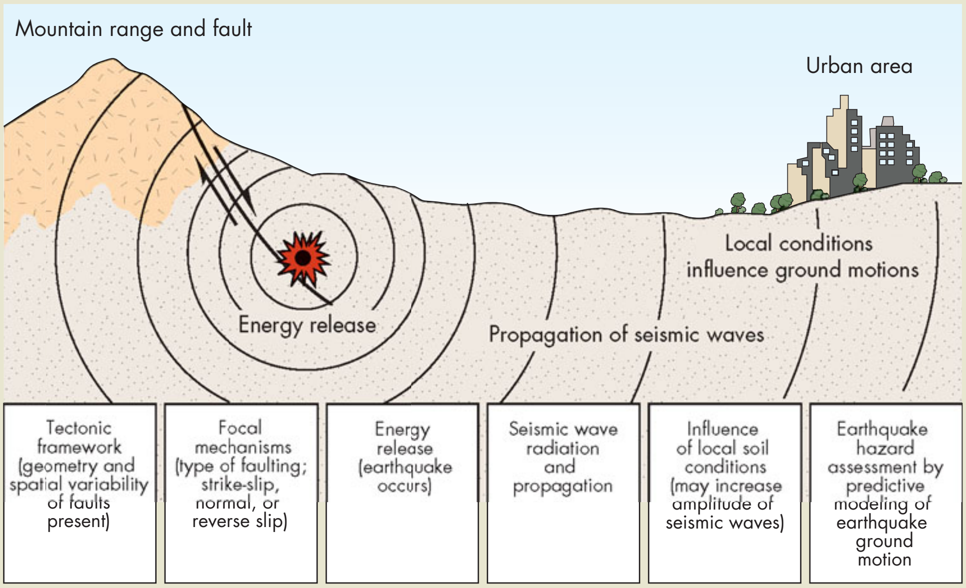
The primary purpose of earthquake hazard assessment is to provide a safeguard against loss of life and major structural failures rather than to limit damage or to maintain functional aspects of society, including roads and utilities.[39] The basic philosophy behind the evaluation of seismic hazard is to have what is known as a **design basis ground motion**, defined as the ground motion that has a 10 percent chance of being exceeded in a 50-year period (equivalent to 1 chance in 475 of being exceeded each year). This is determined in California by a series of maps that show strong-motion peak ground acceleration (PGA) for earthquake waves of a 0.3-second period for one- and two-story buildings and a 1.0-second period for buildings taller than two stories.[40] The U.S. Geological Survey has programs to predict peak acceleration and velocity of shaking through generation of an earthquake-planning scenario for a particular fault. For example, Figure 6.C shows a scenario for a M 7.2 event on the San Andreas fault at San Francisco, California.[41]

Assessment of earthquake hazard at a particular site includes identification of the **tectonic framework** (i.e., geometry and spatial pattern of faults or seismic sources), in order to predict earthquake slip rate and ground motion (Figure 6.D). The process of predicting slip rate and ground motion from a given earthquake may be illustrated by considering a hypothetical example. Figure 6.Ea shows an example of a dam and reservoir site. The objective is to predict strong ground motion at the dam from several seismic sources

Perceived shaking	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential damage	none	none	none	Very light	Light	Moderate	Moderate /Heavy	Heavy	Very Heavy
Peak ACC (%g)	< .17	.17–1.4	1.4–3.9	3.9–9.2	9.2–18	18–34	34–65	65–124	> 124
Peak VEL (cm/s)	< 0.1	0.1–1.1	1.1–3.4	3.4–8.1	8.1–16	16–31	31–66	66–116	> 116
Instrumental intensity	I	II–III	IV	V	VI	VII	VIII	IX	X+

FIGURE 6.C Earthquake planning scenario This scenario is for a M 7.2 event on the San Andreas fault in San Francisco, California. Instrumental intensity refers to the Mercalli Scale (see Table 6.4). *(www.earthquake.usgs.gov)*

FIGURE 6.D Assessment of earthquake hazard One way to assess earthquake hazard is to model ground motion. *(After Vogel, 1988. In A. Vogel and K. Brandes (eds.),* Earthquake Prognostics. *Brannschweig/Weisbaden: Friedr. Vieweg & Sohn, 1–13.)*



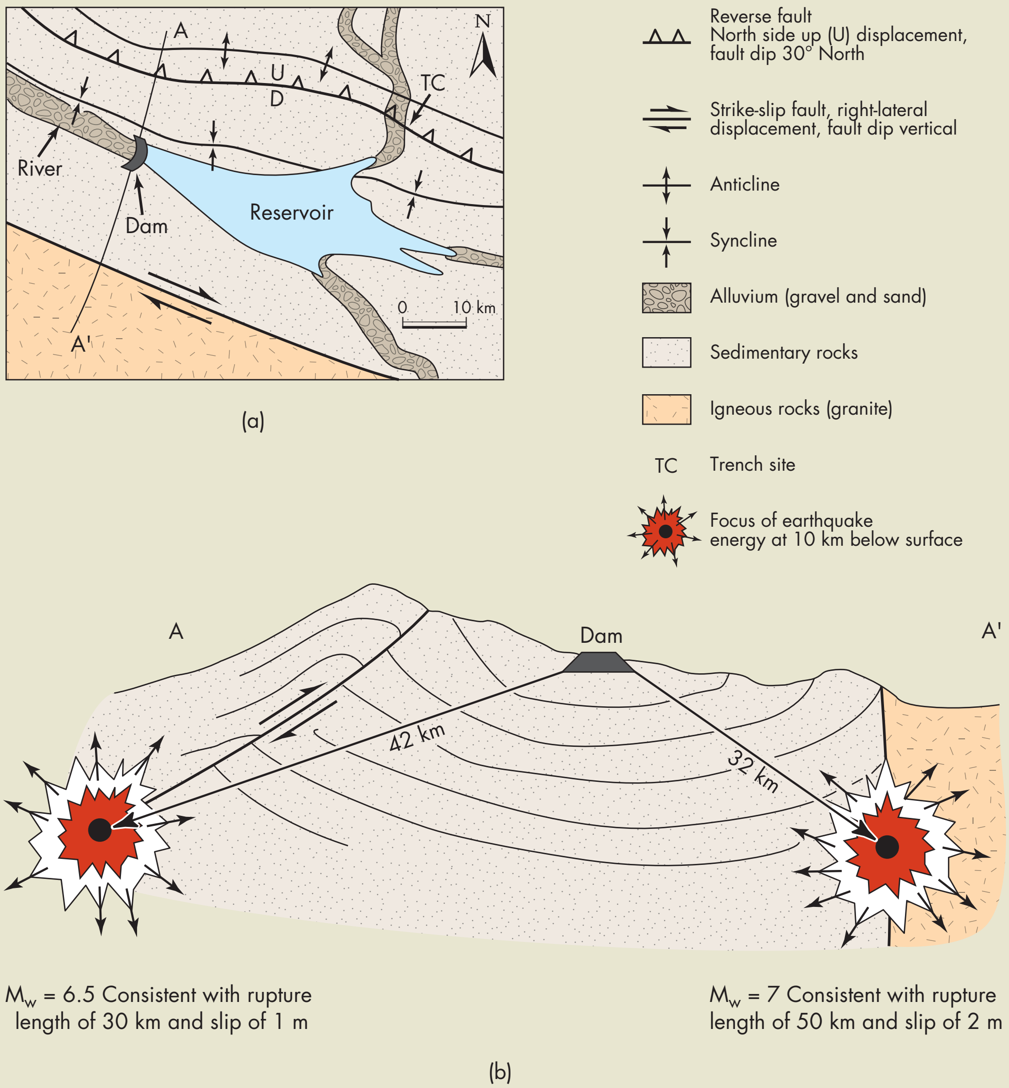


FIGURE 6.E Tectonic framework for a hypothetical dam site (a) Geologic map. (b) Cross section A-A', showing seismic sources and distances of possible ruptures to the dam.

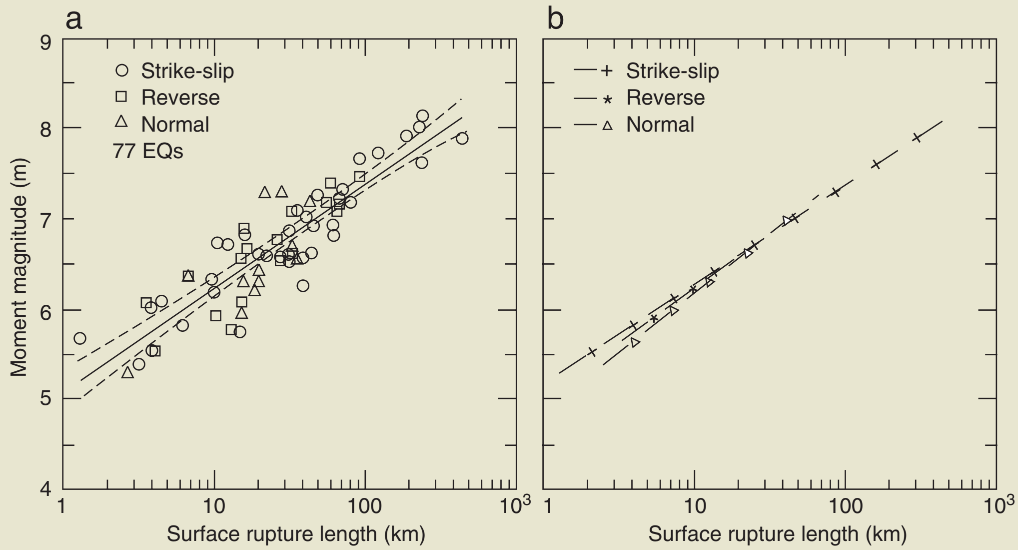
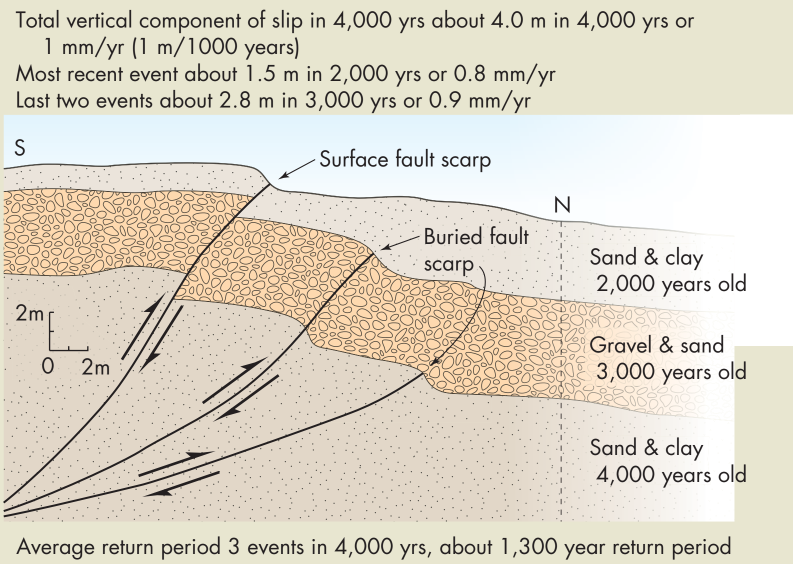


FIGURE 6.F Relationship between moment magnitude of an earthquake and surface rupture length Data for 77 events are shown in (a). The solid line is the "best-fit" or regression line, and dashed lines are error bars at significant difference between the lines. The regression lines for the three types of faults are nearly the same (b). *(After Wells and Coppersmith, 1994. Bulletin of the Seismological Society of America 84:974-1002)*

FIGURE 6.G Trench log The trench log (stratigraphy) for the trench site on Figure 6.Ea.



(i.e., faults) in the area. The tectonic framework shown consists of a north-dipping reverse fault and an associated fold (an anticline) located to the north of the dam, as well as a right-lateral strike-slip fault located to the south of the dam. Figure 6.Eb shows a cross section through the dam, illustrating the geologic environment, including several different Earth materials, folds, and faults. Assuming that earthquakes would occur at depths of approximately 10 km, the distances from the dam to the two seismic sources (the reverse fault and the strike-slip fault) are 42 km and 32 km, respectively. Thus, for this area, two focal mechanisms are possible: reverse faulting and strike-slip faulting.

Another step in the process is to estimate the largest earthquakes likely to occur on these faults. Assume that fieldwork in the area revealed ground rupture and other evidence of faulting in the past, suggesting that, on the strike-slip fault, approximately 50 km of fault length might rupture in a single event, with right-lateral strike-slip motion of 2 m. The

fieldwork also revealed that the largest rupture likely on the reverse fault would be 30 km of fault length, with vertical displacement of about 1.5 m. Given this information, the magnitudes of possible earthquake events can be estimated from graphs such as those shown in **Figure 6.F**.[42] Fifty kilometers of surface rupture are associated with an earthquake of approximately M_W 7. Similarly, for the reverse fault with surface rupture length of 30 km, the magnitude of a possible earthquake is estimated to be M_W 6.5. Notice that, in Figure 6.F, the regression line that predicts the moment magnitude is for strike-slip, normal, and reverse faults. Statistical analyses have suggested that the relation between moment magnitude and length of surface rupture is not sensitive to the style of faulting.[42]

Slip rate (the vertical component) and average return period may be estimated from geologic data collected in a trench excavated across a fault. **Figure 6.G** shows the stratigraphy (trench log) for the site shown in Figure 6.Ea. The slip rate is about 1 mm/yr (1 m/1,000 years), and the average return period is about 1,300 years.

stack of pancakes[7] (also see the case history opening this chapter). This is not to say that the Northridge earthquake was not a catastrophe. It certainly was; the Northridge earthquake left 25,000 people homeless, caused the collapse of several freeway overpasses, injured approximately 8,000 people, and inflicted many billions of dollars in damages to structures and buildings (Figure 6.A). However, since most buildings in the Los Angeles Basin are constructed with wood frames or reinforced concrete, thousands of deaths were avoided in Northridge.

- *Land use planning*, including the siting of important structures such as schools, hospitals, and police stations in areas away from active faults or sensitive Earth materials that are likely to increase seismic shaking. This planning involves zoning the ground's response to seismic shaking on a block-by-block basis. Zoning for earthquakes in land-use planning is necessary because ground conditions can change quickly in response to shaking. In urban areas, where property values may be as high as millions to billions of dollars per block, we need to produce detailed maps of ground response to accomplish zonation. These maps will assist engineers when designing buildings and other structures that can better withstand seismic shaking. Clearly, zonation requires a significant investment of time and money; however, the first step is to develop methods that adequately predict the ground motion from an earthquake at a specific site.
- *Increased insurance and relief measures* to help adjustments after earthquakes. After the 1994 Northridge earthquake, total insurance claims were very large, and some insurance companies terminated earthquake insurance.

We hope to be able to predict earthquakes eventually. The federal plan for issuing prediction and warning is shown in **Figure 6.31**. Notice how it is related to the general flow path for issuance of a disaster prediction shown in Figure 5.14. The general flow of information moves from scientists to a prediction council for verification. Once verified, a prediction that a damaging earthquake of a specific magnitude

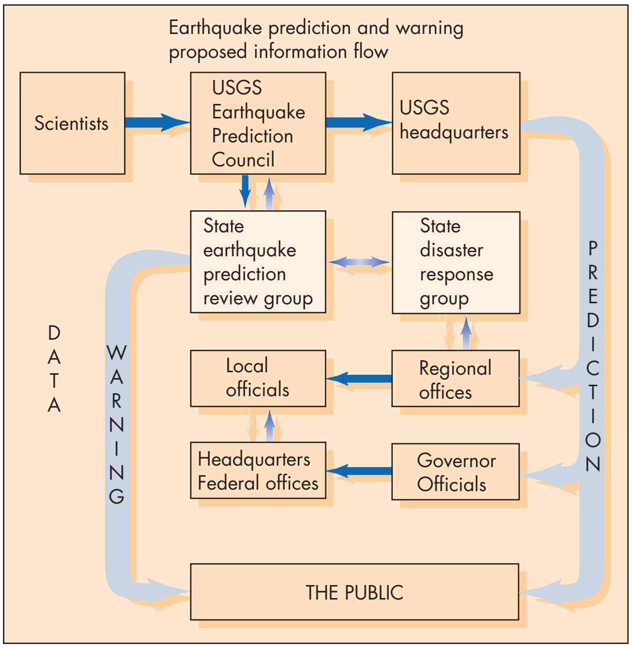


FIGURE 6.31 Issuing a prediction or warning A federal plan for issuance of earthquake predictions and warning: the flow of information. *(From McKelvey, V. E. 1976.* Earthquake Prediction—Opportunity to Avert Disaster. *U.S. Geological Survey Circular 729)*

A Closer Look

The Alaska Earthquake of 2002 and the Value of Estimating Potential Ground Rupture

On November 3, 2002, a magnitude 7.9 earthquake occurred in early afternoon on the Denali fault in south-central Alaska. That event produced approximately 340 km of surface rupture, with maximum right-slip displacement of just over 8 m (Figure 6.H). The earthquake struck a remote part of Alaska where few people live, and, although it caused thousands of landslides and numerous examples of liquefaction and intense shaking, little structural damage and no deaths were recorded.[43]

The Denali fault earthquake demonstrated the value of seismic hazard and earthquake hazard evaluation. The fault was studied in the early 1970s, as part of an evaluation of the Trans-Alaskan pipeline that today supplies approximately 17 percent of the domestic oil supply for the United States. Where the pipeline crosses the Denali fault, geologists determined that the fault zone was several hundred meters wide and might experience a 6 m horizontal displacement from a magnitude 8 earthquake. These estimates were used in the design of the pipeline, which included long, horizontal steel beams with Teflon shoes that allowed the pipeline to slide horizontally approximately 6 m. This was accompanied by the utilization of a zigzag pattern of the pipeline that allowed, along with the steel beams, the horizontal movement (Figure 6.H). The 2002 earthquake occurred within the mapped zone of the fault and sustained about 4.3 m (14 ft) of right-lateral strike-slip. As a result, the pipeline suffered little damage, and there was no oil spill. The cost in 1970 of the engineering and construction was about $3 million. Today, that looks very cost-effective, considering that approximately $25 million worth of oil per day is transported via the pipeline. If the pipeline had been ruptured, the cost of repair and cleanup of the environment might have been several hundred million dollars.[44]

FIGURE 6.H Trans-Alaska oil pipeline survives (M 7.9) earthquake The Alaskan pipeline was designed to withstand several meters of horizontal displacement on the Denali fault. The 2002 earthquake caused a rupture of 4.3 m (14 ft) beneath the pipeline. The built-in bends on slider beams with Teflon shoes accommodated the rupture, as designed. This was strong confirmation of the value of estimating potential ground rupture and taking action to remove the potential threat and damage. *(Alyeska Pipeline Service Company [ASPC])*

would occur at a particular location during a specified time would be issued to state and local officials. These officials are responsible for issuing a warning to the public to take defensive action that, one hopes, has been planned in advance. Potential response to a prediction depends upon lead time, but even a few days would be sufficient to mobilize emergency service, shut down important machinery, and evacuate particularly hazardous areas.

Earthquake Warning Systems

Technically, it is feasible to develop an earthquake warning system that would provide 10 seconds or more warning to California cities before the arrival of damaging earthquake waves from an event several hundred kilometers away. This type of system is based on the principle that the warning sent by a radio signal via satellite relay travels much faster than seismic waves. The Japanese have had a system (with more than 1,000 seismometers) for nearly 20 years that provides earthquake warnings for high-speed trains; train derailment by an earthquake could result in the loss of hundreds of lives. A proposed system for California involves a network of seismometers (there are currently about 300) and transmitters along the San Andreas and other faults. This system would first sense motion associated with a large earthquake and then send a warning to Los Angeles, which would then relay the warning to critical facilities, schools, and the general population (**Figure 6.32**). The warning time would vary from as little as 10 seconds to as long as about 1 minute, depending on the location of the epicenter of the earthquake. This could be enough time for people to shut down machinery and computers and take cover.[45,46] Note that this earthquake warning system is not a prediction tool; it only warns that an earthquake has already occurred.

A potential problem with a warning system is the chance of false alarms. For the Japanese system, the number of false alarms is less than 5 percent. However, because the warning time is so short, some people have expressed concern about whether much evasive action could be taken. There is also concern about liability issues resulting from false alarms, warning system failures, and damage and suffering

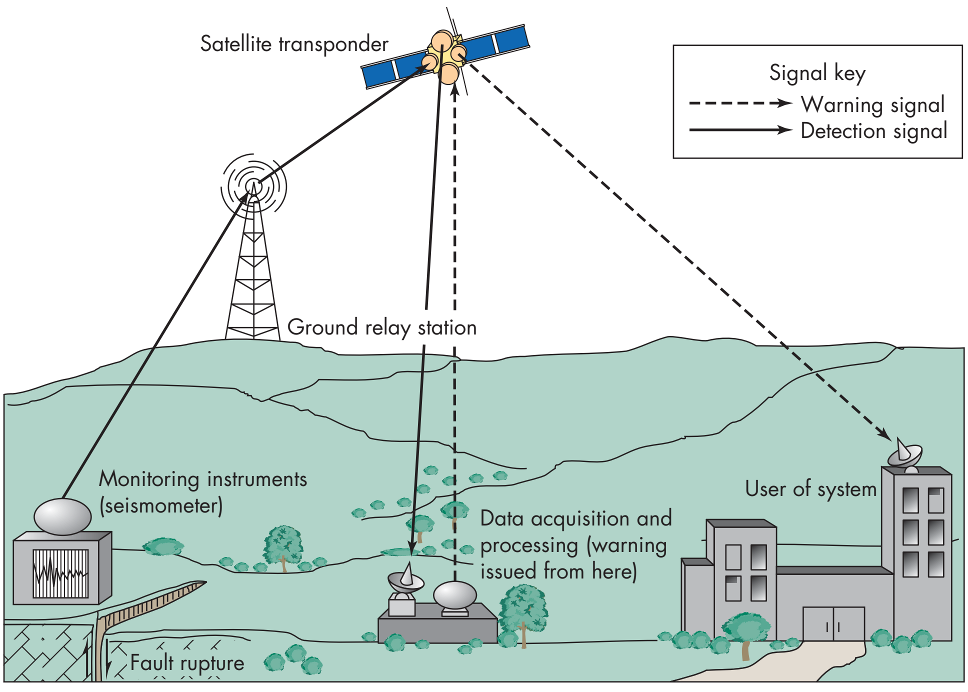


FIGURE 6.32 Earthquake warning Idealized diagram showing an earthquake warning system. Once an earthquake is detected, a signal is sent ahead of the seismic shaking to warn people and facilities. The warning time depends on how far away an earthquake occurs. It could be long enough to shut down critical facilities and for people to take cover. *(After Holden, R., Lee, R., and Reichle, M. 1989.* California Division of Mines and Geology Bulletin *101)*

FIGURE 6.33 Collapse of buildings in Turkey Damage to the town of Golcuk in western Turkey from the M 7.4 earthquake in August 1999. The very old mosque on the left remains standing, whereas many modern buildings collapsed. *(Enric Marti/AP Photo)*

resulting from actions taken as the result of false early warning. The next step for California is to determine how big the seismic network will need to be, install the necessary seismometers, and upgrade the communication system so warnings can be sent out reliably.[46]

Perception of Earthquake Hazard

The fact that terra firma is not so firm in places is disconcerting to people who have experienced even a moderate earthquake. The large number of people, especially children, who suffered mental distress after the San Fernando and Northridge earthquakes attests to the emotional and psychological effects of earthquakes. These events were sufficient to influence the decision of a number of families to move away from Los Angeles.

The Japanese were caught off guard by the 1995 Kobe earthquake, and the government was criticized for not mounting a quick and effective response. Emergency relief did not arrive until about 10 hours after the earthquake! They evidently believed that their buildings and highways were relatively safe, compared with those that had failed in Northridge, California, a year earlier.

As mentioned earlier, a remarkable sequence of earthquakes in Turkey terminated in 1999 with two large damaging earthquakes (Figure 6.30). The first occurred on August 17 and leveled thousands of concrete buildings. As a result of the earthquake, 600,000 people were left homeless, and approximately 38,000 people died. Some of the extensive damage to the town of Golcuk in western Turkey is shown in **Figure 6.33**. Note that the very old mosque on the left is still standing, whereas many modern buildings collapsed, suggesting that earlier construction was more resistant to earthquakes. Although Turkey has a relatively high standard for new construction to withstand earthquakes, there is fear that poor construction was a factor in the collapse of the newer buildings, due to the intense seismic shaking. It has been alleged that some of the Turkish contractors bulldozed the rubble from collapsed buildings soon after the earthquake, perhaps in an effort to remove evidence of shoddy construction. If that allegation is true, these contractors also tied up bulldozers that could have been used to help rescue people trapped in collapsed buildings.

The lessons learned from Northridge, Kobe, Turkey, Pakistan, and Haiti were bitter ones that illuminate our modern society's vulnerability to catastrophic loss

from large earthquakes. Older, unreinforced concrete buildings or buildings not designed to withstand strong ground motion are most susceptible to damage. In Kobe, reinforced concrete buildings constructed post-1990 with improved seismic building codes experienced little damage, compared with those constructed in the mid-1960s or earlier. Minimizing the hazard requires new thinking about the hazard. In addition, microzonation is instrumental in the engineering response to design structures that are less vulnerable to ground motion from earthquakes.

Personal and Community Adjustments: Before, During, and After an Earthquake

A group of individuals living in an area define a community, whether it is a village, town, or city. In areas with an earthquake hazard, it is important for people to prepare for the hazard in terms of what can be done before, during, and after an earthquake.

At the community level, one important aspect of earthquake preparedness is enforcing building codes, such as the Uniform Building Code of California. The objective of the earthquake section of the code is to provide safeguards against loss of life and major structural failures through better design of buildings to allow them to better withstand earthquake shaking. Another important task is the inspection of older buildings to determine if a "retrofit" is necessary to increase the strength of the building in order to better withstand earthquakes. In fact, the state of California has regulated building retrofits. A recent study concluded that many of the hospitals in southern California are in need of extensive and costly retrofitting.

Education is also an important component of earthquake preparedness at the community level. Government, state, and local agencies prepare pamphlets and videos concerning the earthquake hazard and help ensure that this information is distributed to the public. Workshops and training meetings concerning the most up-to-date information on how to minimize earthquake hazards are available to professionals in engineering, geology, and planning. A great deal of information at the community level is also available on the World Wide Web from a variety of sources, including the U.S. Geological Survey and scientific organizations, such as the Southern California Earthquake Center, as well as other agencies interested in earthquake hazard reduction.[47]

In schools, it is important to practice what is sometimes called the "earthquake drill": Everyone pretends that an earthquake is happening, and students "duck, cover, and hold." After about 15 or 20 seconds, students emerge from their duck-and-cover location, take five slow, deep breaths, practice calming down, and then walk to a designated safe area.

A massive earthquake drill was held on November 13, 2008, for the Los Angeles region. Known as the Great Southern California Shake Out, the drill involved millions of people. The scenario (potential) earthquake was a M 7.8 event on the southern San Andreas fault that resulted in 2,000 deaths, 50,000 injuries, and $200 billion in losses, with extensive and long-lasting disruption. The drill helped evaluate emergency preparation for a large earthquake and made people more aware of what we know is coming. We will know how successful the drill was after the real event occurs.

At the personal level in homes and apartments, it is estimated that billions of dollars of damages from earthquakes could be avoided if our buildings and contents were better secured to withstand shaking from earthquakes. Before an earthquake occurs, homeowners and apartment dwellers should complete a thorough check of the building, including rooms, foundations, garages, and attics. The following are some items of a home safety check:[47]

- Be sure your chimney has been reinforced to withstand shaking from earthquakes. After the 1994 Northridge earthquake, one of the most commonly observed types of damage was collapsed chimneys.
- Be sure your home is securely fastened to the foundation and that there are panels of plywood between the wooden studs in walls. Make sure that large openings, such as garage doors with a floor above, are adequately braced.
- Within the house, be sure that anything that is heavy enough to hurt you if it falls on you, or is fragile and expensive, is secured. There are ways to secure tabletop objects, television sets, tall furniture, and cabinet doors.
- Large windows and sliding doors may be covered with strong polyester (Mylar) films to make them safer and reduce the hazard from broken glass that is shattered during earthquakes.
- Ensure that your gas water heater is strapped to the building so that it will not fall over and start a fire. If necessary, change to flexible gas connections that can withstand some movement.

Probably the most important and rational thing you can do before an earthquake is to prepare a plan of exactly what you will do if a large earthquake occurs. This might include the following points:[47]

- Teach everyone in your family to "duck, cover, and hold." For each room in your home, identify safe spots, such as under a sturdy desk or table or near strong interior walls.
- Instruct everyone who might be home how to turn off the gas. However, the gas should be turned off only if a leak is detected through either hearing or smelling the leaking gas.
- After an earthquake, out-of-area phone calls are often much easier to place and receive than local calls. Therefore, establish an out-of-area person who can be contacted.
- Be sure you have necessary supplies, such as food, water, first-aid kit, flashlights, and some cash to tide you over during the emergency period when it may be difficult to obtain some items.
- Canvass your neighborhood and identify elderly or disabled neighbors who may need your help in the event of an earthquake and help educate others in the neighborhood about how to prepare their own plans.

During an earthquake, the strong ground motion will greatly restrict your motion, and, as a result, your strategy should be to "duck, cover, and hold." Given your knowledge of earthquakes, you may also try to recognize how strong the earthquake is likely to be and to predict what may happen during the event. For example, you know there will be several types of waves, including P, S, and R waves. The P waves will arrive first, and you may even hear them coming. However, the S and R waves, which soon follow, have bigger displacement and cause most of the damage. The length of shaking during an earthquake will vary with the magnitude. For example, during the 1994 Northridge earthquake, the shaking lasted approximately 15 seconds, but the time of shaking in a great earthquake may be much longer. For example, during the 1906 San Francisco earthquake, shaking lasted nearly 2 minutes. In addition to the "duck, cover, and hold" strategy, you need to remain calm during an earthquake and try to protect yourself from appliances, books, and other materials possibly sliding or flying across the room. A good strategy would be to crouch under a desk or table, roll under a bed, or position yourself in a strong doorway. During the earthquake, there may be explosive flashes from transformers and power poles, and you must obviously avoid downed power lines. At all costs, resist the natural urge to panic.[47]

After the shaking stops, take your deep breaths and organize your thinking in accordance with the plan you developed. Check on your family members and neighbors, and check for gas leaks and fires. Your telephones should be used only for emergency calls. Examine your chimney, as chimneys are particularly prone to failure from earthquakes. The chimney may separate from the roof or the walls along the side of the chimney. If you are caught in a theater or stadium during a large earthquake, it is important to remain in your seat and protect your head and neck with your arms; do not attempt to leave until the shaking has stopped. Remain calm and walk out slowly, keeping a careful eye out for objects that have fallen or may fall. If you are in a shopping mall, it is important to "duck, cover, and hold" away from glass doors and display shelves of books or other objects that could fall on you. If you are outdoors and an earthquake occurs, it is prudent to move to a clear area where you can avoid falling trees, buildings, power lines, or other hazards. If you are in a mountainous area, be aware of landslide hazards, since an earthquake may generate slides that occur during and for some time after the earthquake. If you are in a high-rise building, you need to "duck, cover, and hold," as in any other indoor location, avoiding any large windows. It is likely that the shaking may activate fire alarms and water sprinkler systems. Streets lined with tall buildings are very dangerous locations during an earthquake; glass from these buildings often shatters and falls to the street below, and the razor-sharp shards can cause serious damage and death to people below.[47]

Finally, after an earthquake, be prepared for aftershocks. There is a known relationship between the magnitude of the primary earthquake and the distribution of aftershocks in hours, days, months, or even years following the earthquake. If the earthquake has a magnitude of about 7, then several magnitude 6 aftershocks can be expected. Many magnitude 5 and 4 events are likely to occur. In general, the number and size of aftershocks decrease with time from the main earthquake event, and the most hazardous period is in the minutes, hours, and days following the main shock.

The good news concerning living in earthquake country in the United States is that large earthquakes are survivable. Our buildings are generally constructed to withstand earthquake shaking, and our woodframe houses seldom collapse. It is, however, important to be well informed and prepared for earthquakes. For that reason, it is extremely important to develop and become familiar with your personal plan of what to do before, during, and after an earthquake.

Making The Connection

Linking the Opening Case History About Recent Earthquakes in Italy and Haiti to the Fundamental Concepts

Consider and discuss the following questions:

1. What is the main lesson from the recent earthquakes in Italy and Haiti?
2. How are science and values linked to the two earthquakes discussed?
3. Italy is a wealthy country compared to Haiti. How important is the wealth of a country to reducing the earthquake hazard?

Summary

Large earthquakes rank among nature's most catastrophic and devastating events. Most earthquakes occur in tectonically active areas where lithospheric plates interact along their boundaries, but some large damaging intraplate earthquakes also occur.

A fault is a fracture or fracture system along which rocks have been displaced. Strain builds up in the rocks on either side of a fault as the sides pull in different directions. When the stress exceeds the strength of the rocks, they rupture, giving rise to seismic, or earthquake, waves that shake the ground.

Strike-slip faults exhibit horizontal displacement and are either right or left lateral. Dip-slip faults exhibit vertical displacement and are either normal or reverse. Some faults are buried and do not rupture the surface, even when their movement causes large earthquakes. Recently, a new fundamental Earth process known as slow earthquakes has been discovered. Slow earthquakes may last from days to months, with large areas of fault rupture but small displacements.

A fault is usually considered active if it has moved during the past 10,000 years and potentially active if it has moved during the past 1.65 million years. Some faults exhibit tectonic creep, a slow displacement not accompanied by felt earthquakes.

The area within Earth where fault rupture begins is called the focus of the earthquake and can be from a few kilometers to almost 700 km (435 mi) deep. The area of the surface directly above the focus is called the epicenter. Seismic waves of different kinds travel away from the focus at different rates; much of the damage from earthquakes is caused by surface waves. The severity of shaking of the ground and buildings is affected by the frequency of the seismic waves and by the type of Earth material present. Buildings on unconsolidated sediments or landfill, which tend to amplify the shaking, are highly subject to earthquake damage.

The magnitude of an earthquake is a measure of the amount of energy released. The measure of the intensity of an earthquake, the Modified Mercalli Scale, is based on the severity of shaking as reported by observers and varies with proximity to the epicenter and local geologic and engineering features. Following an earthquake, shake maps, based on a dense network of seismographs, can quickly show areas where potentially damaging shaking occurred. This information is needed quickly to assist emergency efforts. Ground acceleration during an earthquake is important information necessary to design structures that can withstand shaking.

The hypothesized earthquake cycle for large earthquakes has four stages. A period of seismic inactivity, during which elastic strain builds up in the rocks along a fault, is followed by a period of increased seismicity as the strain locally exceeds the strength of the rocks, initiating local faulting and small earthquakes. The third stage,

which does not always occur, consists of foreshocks. The fourth stage is the major earthquake, which occurs when the fault segment ruptures, producing the elastic rebound that generates seismic waves.

Human activity has caused increasing earthquake activity by loading Earth's crust through construction of large reservoirs; by disposal of liquid waste in deep disposal wells, which raises fluid pressures in rocks and facilitates movement along fractures; and by setting off underground nuclear explosions. The accidental damage caused by the first two activities is regrettable, but what we learn from all the ways we have caused earthquakes may eventually help us to control or stop large earthquakes.

Effects of earthquakes include violent ground motion, accompanied by fracturing, which may shear or collapse large buildings, bridges, dams, tunnels, and other rigid structures. Other effects include liquefaction, landslides, fires, and regional subsidence and uplift of landmasses, as well as regional changes in groundwater levels and surface water flow. Large to great submarine earthquakes can generate a damaging catastrophic tsunami (see Chapter 7).

Prediction of earthquakes is a subject of serious research. To date, long-term and medium-term earthquake prediction, based on probabilistic analysis, has been much more successful than short-term prediction. Long-term prediction provides important information for land-use planning, developing building codes, and engineering design of critical facilities. Some scientists believe that we will eventually be able to make long-, medium-, and short-range predictions, based on previous patterns and frequency of earthquakes, as well as by monitoring the deformation of land, the release of radon gas, and existing seismic gaps. Although not currently being pursued, reports suggest that anomalous animal behavior before an earthquake may offer potential aid in earthquake prediction. A potential problem of predicting earthquakes is that their pattern of occurrence is often variable, with clustering or sequencing of events being separated by longer periods of time with reduced earthquake activity.

Reduction of earthquake hazards will be a multifaceted program, including recognition of active faults and Earth materials sensitive to shaking and development of improved ways to predict, control, warn of and adjust to earthquakes, including designing structures to better withstand shaking. Many communities in the U.S. and other countries are developing emergency plans to respond to a predicted or unexpected catastrophic earthquake. Seismic zoning, including microzonation and other methods of hazard reduction, are active areas of research. At a personal level, there are steps an individual can take before, during, and after an earthquake to reduce the hazard and ease recovery.

Revisiting Fundamental Concepts

Human Population Growth Human population growth, especially in large cities in seismically active regions, is placing more and more people and property at risk from earthquakes.

Sustainability Minimizing the damages from earthquakes to public and private property is a component of sustainable development. The goal is to produce stable communities that are less likely to experience catastrophic losses as a result of poor earthquake preparation.

Earth as a System Earthquakes are produced by Earth's internal tectonic systems. Landforms, including ocean basins and mountains, are the products of continental movement and resultant earthquakes. Mountains cause changes to atmospheric processes that create deserts and regional patterns of rainfall and, thus, affect vegetation and erosion. This is an example of the principle of environmental unity: One change, in this case the development of mountains, causes a chain of other events.

Hazardous Earth Processes, Risk Assessment, and Perception We cannot control processes that produce earthquakes, but how we perceive the earthquake hazard greatly influences the actions we take to minimize the risk of loss of life. If we perceive earthquakes as a real risk to our lives and those of our family and friends, we will take the necessary steps to prepare for future earthquakes.

Scientific Knowledge and Values Scientific knowledge about earthquakes in terms of how they are produced, where and why they occur, and how to design buildings to better withstand earthquake shaking has grown dramatically in recent years. Important lessons were learned from the 1999 earthquakes in Turkey that killed about 38,000 people. Turkey has relatively high building standards, and more buildings should have survived the quakes. Some people believe that improper construction contributed significantly to the loss of buildings. Contractors may have destroyed evidence of inadequate construction after the earthquake occurred. Community values result in building regulations that help reduce earthquake losses. If buildings are properly constructed to withstand earthquakes, then loss of life may be greatly reduced in the future.

Key Terms

active fault (p. 181)
design basis ground motion (p. 209)
dilatancy-diffusion model (p. 197)
dilate (p. 197)
directivity (p. 190)
earthquake (p. 179)
earthquake cycle (p. 195)
earthquake segment (p. 181)
epicenter (p. 170)
fault (p. 179)
fault segmentation (p. 181)
fault-valve mechanism (p. 197)
fault zone (p. 181)
fluid pressure (p. 197)
focus (p. 170)
liquefaction (p. 199)
material amplification (p. 189)
Modified Mercalli Scale (p. 173)
moment magnitude (p. 170)
P wave (p. 184)
recurrence interval (p. 182)
shake map (p. 173)
slip rate (p. 182)
slow earthquake (p. 184)
surface wave (p. 184)
S wave (p. 184)
tectonic creep (p. 184)
tectonic framework (p. 209)

Review Questions

1. What is the difference between the focus and the epicenter of an earthquake?
2. How is Richter magnitude determined?
3. What are slow earthquakes?
4. What factors determine the Modified Mercalli Scale?
5. What are the main differences between the Richter, moment magnitude, Modified Mercalli, and instrumental scales?
6. Define *fault*.
7. What are the major types of faults?
8. What is the difference between an anticline and a syncline?
9. Define *active fault*.
10. What is tectonic creep?
11. What are the main types of seismic wave?
12. Describe the motions of P, S, and R waves. How do their physical properties account for their effects?
13. What is a shake map, how is it produced, and why are they important?
14. What is material amplification?
15. Define the earthquake cycle and illustrate it with a simple example.
16. How has human activity caused earthquakes?
17. What are some of the major effects of earthquakes?
18. What is supershear?
19. What are some of the precursory phenomena likely to assist us in predicting earthquakes?
20. What are the major goals of earthquake hazard-reduction programs?
21. What are the main adjustments people make to seismic activity and the occurrence of earthquakes?

Critical Thinking Questions

1. Assume that you are working for the Peace Corps and are in a developing country where most of the homes are built out of unreinforced blocks or bricks. There has not been a large damaging earthquake in the area for several hundred years, but earlier there were several earthquakes that killed thousands of people. How would you present the earthquake hazard to the people living where you are working? What steps might be taken to reduce the hazard?
2. You live in an area that has a significant earthquake hazard. There is ongoing debate as to whether an earthquake warning system should be developed. Some people are worried that false alarms will cause a lot of problems, and others point out that the response time may not be very long. What are your views? Do you think it is a responsibility of public officials to finance an earthquake warning system, assuming such a system is feasible? What are potential implications if a warning system is not developed, and a large earthquake results in damage that could have partially been avoided with a warning system in place?

Companion Website www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

2004 Indonesian tsunami Damage in Banda Acehi, Indonesia, from the 2004 tsunami. *(Ahmad Yusni/epa/Corbis)*

7

Tsunami

Learning Objectives

Tsunami, defined as great sea waves produced by submarine earthquakes, volcanic eruptions, or landslides, have long been known to cause disasters and catastrophes, but, until recently, the hazard posed by tsunami has been underestimated. For years, scientists attempted to get public officials to expand tsunami warning systems to ocean basins outside of the Pacific Ocean. It took the catastrophic deaths and devastation of the Indonesian tsunami of 2004 for many governments and communities to take the tsunami hazard seriously. However, as often occurs after disasters and catastrophes, translating the increased hazard awareness into improved warning, preparedness, and mitigation is proceeding at a relatively slow pace. This chapter will examine the natural tsunami process and assess the hazard that these waves pose to people. Your goals in reading the chapter will be:

- **Understand the process of tsunami formation and development**
- **Understand the effects of tsunami and the hazards they pose to coastal regions**
- **Know what geographic regions are at risk for tsunami**
- **Recognize the linkages between tsunami and other natural hazards**
- **Know what nations, communities, and individuals can do to minimize the tsunami hazard**

Case History

Indonesian Tsunami

Prior to Sunday, December 26, 2004, few people knew what the Japanese word *tsunami* means. That changed in the span of only a few hours, as close to 250,000 people were killed, many hundreds of thousands injured, and millions were displaced in over a dozen countries surrounding the Indian Ocean. With no warning system in place, residents of coastal area after coastal area around the Indian Ocean were struck by a series of tsunami waves without notice.

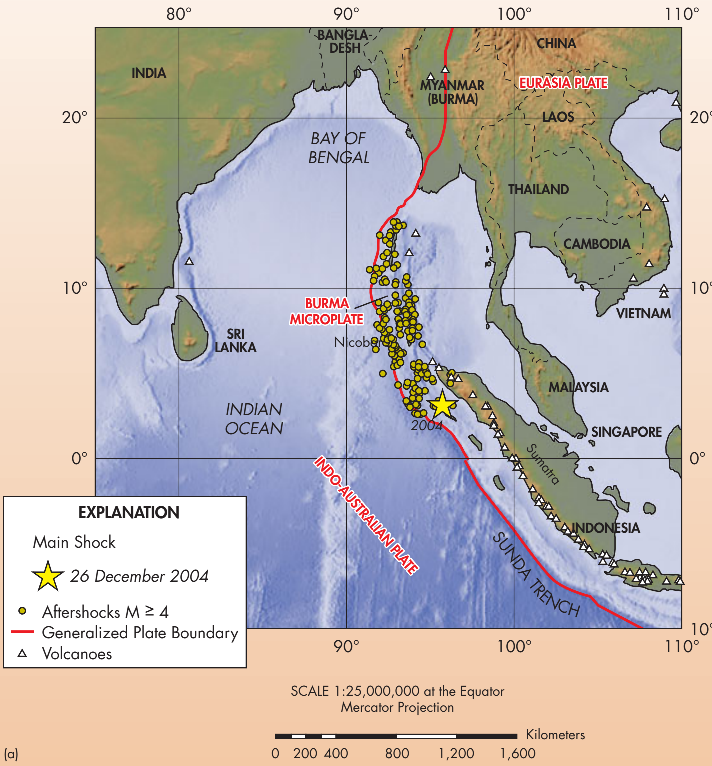


FIGURE 7.1 Geologic setting of the Indonesian tsunami The gold star locates the epicenter of the main shock of the M 9.1 earthquake on December 26, 2004. *(Modified after U.S. Geological Survey)*

The source of this tsunami was the largest earthquake on Earth in the past 4 decades that struck on the morning of December 26, just off the west coast of the Indonesian island of Sumatra (**Figure 7.1**). At a magnitude of about 9.1, this earthquake caused the most damaging tsunami in recorded history.[1] Great earthquakes of this magnitude occur along tectonic plate boundaries where one plate is subducted below another. In this case, the Indian and Australian plates are being subducted to the northeast beneath the Burma microplate. In this earthquake, the Burma microplate moved about 20 m (65 ft) to the west–southwest, along a gently inclined subduction zone (**Figure 7.2**).[1] Because this was a large amount of displacement along the thrust faults in the subduction zone, geologists classify this earthquake as a "megathrust event." Seismic waves generated by the rupture caused several minutes of shaking on nearby islands. The total length of the rupture along the subduction zone was over 1,500 km (930 mi), about the length of the state of California.[1] Not only did the seafloor shift about 20 m (65 ft) horizontally, it also rose several meters vertically.[1] Displacement of the sea bottom disturbed and displaced the overlying waters of the Indian Ocean, and a series of tsunami waves were generated. The effect is like throwing a large boulder in your bathtub and watching the rings or waves of water spread out. In this case, though, the boulder came up from the bottom, but the result was the same and waves radiated outward, moving at high speed across the Indian Ocean (**Figure 7.3**, page 226).

Unlike in the Pacific Ocean, there was no tsunami warning system for the Indian Ocean, and people were mostly caught by surprise. Scientists on duty at the Pacific Tsunami Warning Center in Hawaii recognized that the earthquake could potentially produce a tsunami, but the geophysical techniques to calculate the size of earthquakes of such magnitude were

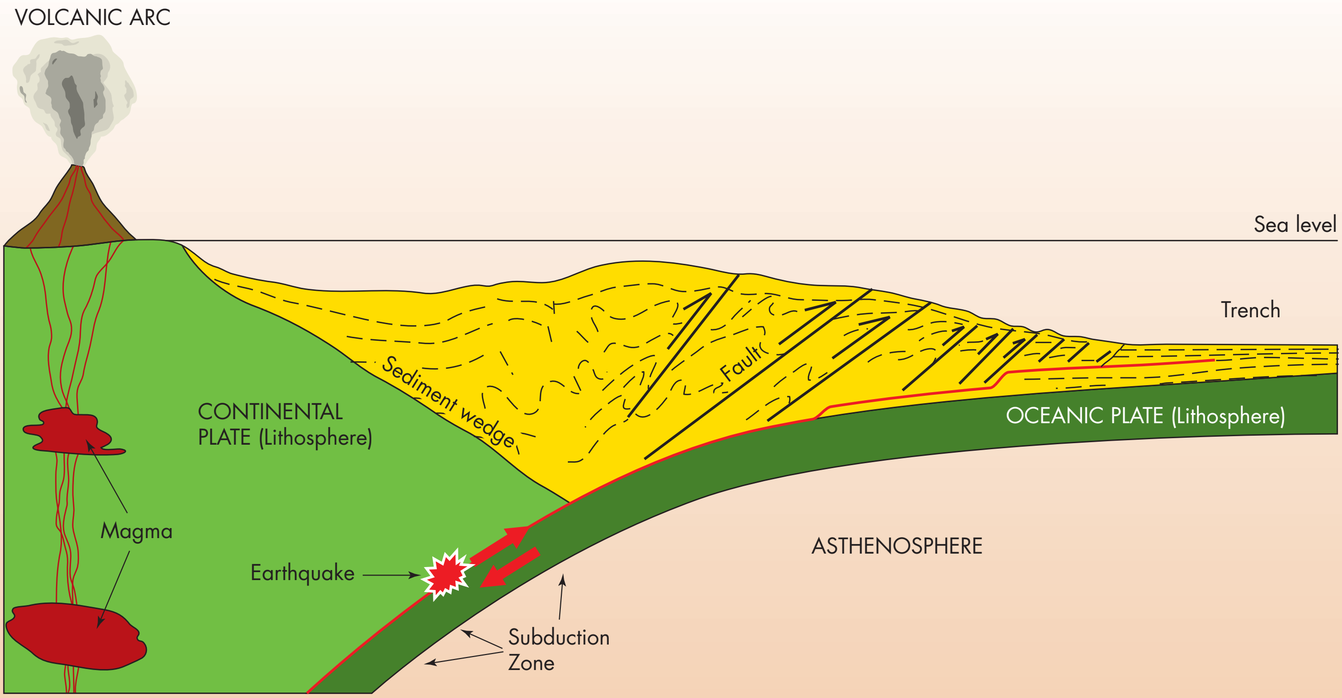


FIGURE 7.2 Earthquake in subduction zone Idealized cross section of where a subduction zone earthquake might occur. *(Modified from United Kingdom Hydrographic Office)*

not immediately available to them.[2] Once they determined that a tsunami was likely, the scientists managed to contact other scientists in Indonesia and have the U.S. State Department relay their concerns to some nations surrounding the Indian Ocean. Unfortunately, the warnings did not reach authorities in time to take action, and, even if they had, there was no system in place for directly notifying coastal residents. Had it been possible for warnings to be received, tens of thousands of lives could have been saved. This is because the tsunami waves took several hours to reach some of the coastlines where people died (Figure 7.3). Even a warning of a half hour or so would have been sufficient to move many people from low-lying coastal areas.[3] The first sensor on the seafloor to detect a tsunami in the Indian Ocean was installed in 2006, and others have followed. Sirens are now in place in some coastal areas around the Indian Ocean to warn people when a tsunami is coming.

Over three-quarters of the deaths were in Indonesia, which experienced both the intense shaking from the earthquake and the inundation by tsunami waves within less than an hour. In contrast, the first tsunami wave took about 2 hours to reach Sri Lanka and India, where many thousands died, and about 7 hours to reach Somalia on the west coast of Africa (Figure 7.3). The first of many tsunami waves reached other locations earlier or later, depending on their distance from the rupture in the subduction zone.

At the northern tip of the island of Sumatra, the Indonesian provincial capital of Banda Aceh was nearly destroyed (**Figure 7.4**, page 227). Destruction was caused by shaking from the earthquake, the force of the tsunami waves, and flooding as the land subsided following the earthquake. Coastal subsidence of a tectonic plate is common in megathrust events.

Tourist areas in the region were hard hit, especially in Thailand, where several thousand tourists from Europe, the United States, and elsewhere were killed. Most visitors, and many first-generation residents, were unfamiliar with tsunamis. They did not know how to recognize that a tsunami was about to take place or what to do if one occurred. This was true for many people in Phuket, Thailand (**Figure 7.5**, page 228). Some people seemed to be mesmerized by the approaching waves, while others ran in panic.

On some coastlines, everything wasn't quite as bleak. In Thailand, a 10-year-old British girl sounded the warning in time for 100 people to evacuate a resort beach. Only a few weeks before going to Thailand, she had received a lesson in school about plate tectonics, earthquakes, and tsunami. As part of that lesson, she

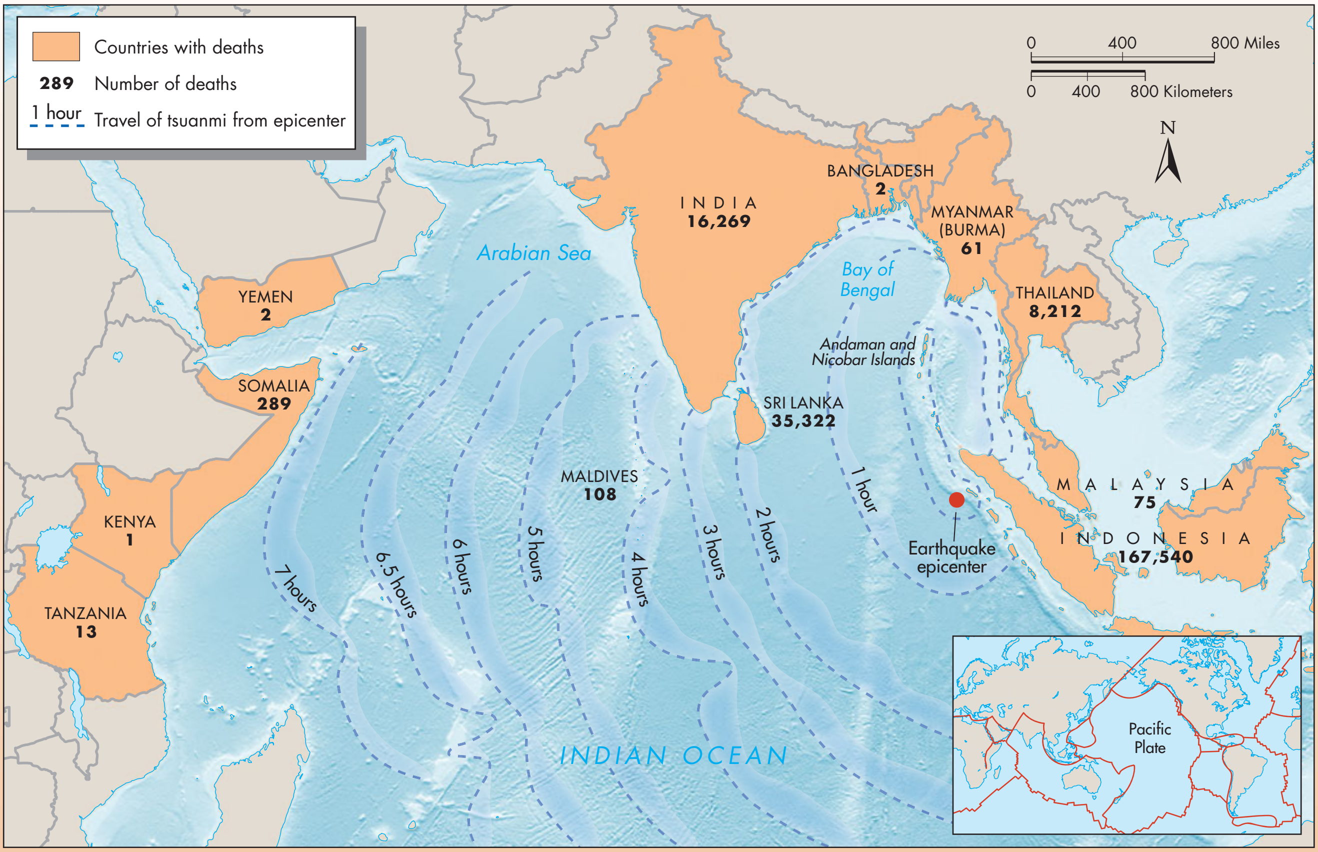


FIGURE 7.3 2004 tsunami killed people on both sides of the Indian Ocean Map showing the path of the tsunami produced by a M 9.1 earthquake off the east coast of Sumatra, Indonesia, on December 26, 2004. Shown with blue dashed lines is the location of the lead tsunami wave each hour after the earthquake. Note that the tsunami waves took approximately 7 hours to reach Somalia on Africa's east coast. Most deaths were in Indonesia, where the first local tsunami wave arrived an hour or less after the earthquake. The number of deaths shown in each country is the total number of people dead or still missing. *(Casualties summarized in Telford, J., and Cosgrave, J. 2006.* Joint Evaluation of the International Response to the Indian Ocean Tsunami: Synthesis report. *London: Tsunami Evaluation Coalition; Tsunami travel time data from NOAA)*

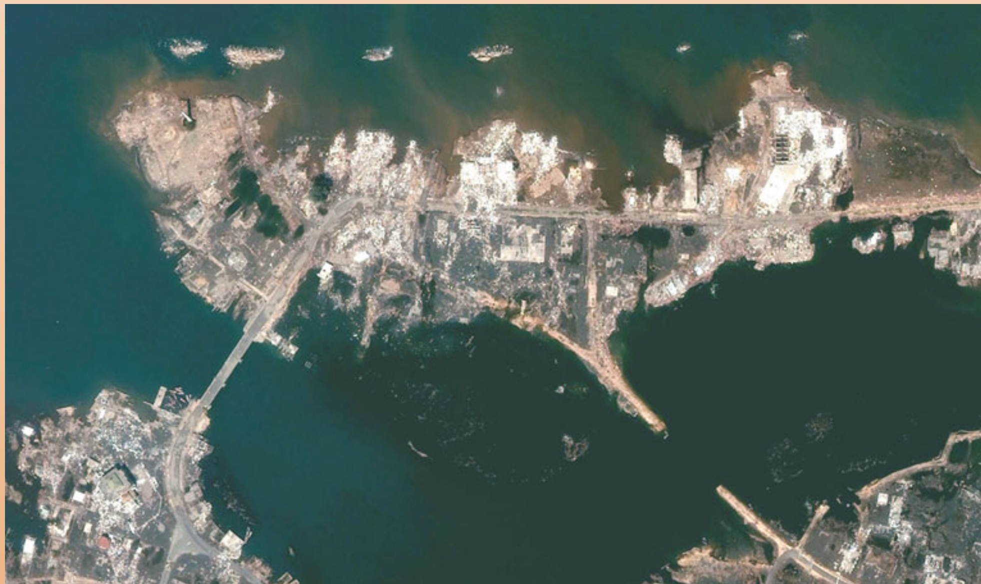
learned that, sometimes, the sea recedes prior to the arrival of a tsunami wave. That is precisely what she observed, and her screaming to get off the beach eventually convinced her mother and others to take action. Thanks to her persistence, the beach was successfully evacuated. Her mother later stated that she did not even know what a tsunami was, but that her daughter's school lesson had saved the day, for them at least.

On another beach in Sri Lanka, a scientist on vacation witnessed a small wave rise up and inundate the hotel swimming pool. In the next 20 minutes, the sea level dropped by around 7 m (23 ft). The scientist recognized these events as a sign that a big wave was coming and sounded the alarm. A hotel employee then used a megaphone to warn people to get off the beach. Many people had gone down to the beach out of curiosity to see the exposed seafloor. Shortly thereafter, the sea rose 7 m (23 ft) above its normal level. Fortunately, most people were either near hotel stairs or had escaped to higher floors. None of the staff or guests drowned, but several people on the ground floor were swept out and survived only by clinging to palm trees in the hotel garden.[4]

In the Andaman and Nicobar Islands in the northeastern Indian Ocean, as well as in parts of Indonesia, some native people have a collective memory of tsunamis. When the earthquake occurred, they applied that knowledge and moved to high ground, saving entire small tribes on some islands.

In Khao Lak, Thailand, it was elephants, not people, who sounded the warning and saved lives in the 2004 tsunami.[5] The elephants, which normally give tourists rides, started

(a)



(b)

FIGURE 7.4 Nearly complete destruction associated with Indonesian tsunami of 2004 (a) Satellite view of Banda Aceh, the Indonesian provincial capital on the northern end of the island of Sumatra, before the earthquake and tsunami of December 26, 2004. *(Digital Globe)* (b) Two days after the tsunami, it is apparent that nearly all the development has been damaged or destroyed. Note that the shoreline at the top of the photograph has been extensively eroded, leaving behind only a few small islands. Large parts of the city flooded because of subsidence caused by the earthquake that combined with inundation from the tsunami. *(Digital Globe)*

trumpeting about the time the M 9.1 earthquake occurred in the subduction zone over 600 km (370 mi) to the west. The elephants became agitated again about 1 hour later. Those elephants that were not taking tourists for rides broke loose from their strong chains and headed inland. Other elephants carrying tourists on their backs ignored their handlers and climbed a hill behind the resort beach where about 4,000 people were killed by the tsunami. When handlers recognized the advancing tsunami, they got other elephants to lift tourists onto their backs with their trunks and proceed inland. The elephants did so, even though they were only accustomed to people mounting them from a wooden platform. Tsunami waves then surged about 1 km (0.5 mi) inland. The elephants stopped just beyond where the waves ended their destructive path.

The question is: Did the elephants know something that people did not? Animals have sensory ability that differs from humans. It's possible the elephants heard the earthquake because earthquakes produce sound

FIGURE 7.5 Tourists running for their lives Man in foreground is looking back at a brown wave of the 2004 Indonesian tsunami rushing toward him. The wave is higher than the building behind him at this Phuket, Thailand, resort. Many people living there, as well as the tourists, did not initially think the wave would inundate the area where they were, and, when the waves arrived, they thought they would be able to outrun the rising water. In some cases, people did escape, but all too often they drowned. *(John Russell/ZUMA Press)*

waves with low tones referred to as *infrasonic sound*. Some people can sense infrasonic sound, but they don't generally perceive it as a hazard. The elephants may also have sensed the motion as the land vibrated from the earthquake. In either case, the elephants fled inland away from the advancing tsunami. Although the link between the elephants' sensory ability and their behavior is still speculative, the actions of the elephants nevertheless saved at least a dozen lives.[5]

Numerous reports received after the 2004 Indonesian tsunami indicate the vital role of education in tsunami preparedness. Thousands of lives

7.1 Introduction

Tsunami (the Japanese word for "large harbor waves") are produced by the sudden vertical displacement of ocean water.[3] These waves are a serious natural hazard that can cause a catastrophe thousands of kilometers from where they originate. They may be triggered by several types of events, including a large earthquake that causes a rapid uplift or subsidence of the seafloor; an underwater landslide that may be triggered by an earthquake; the collapse of part of a volcano that slides into the sea; a submarine volcanic explosion; and an impact in the ocean of an extraterrestrial object, such as an asteroid or comet. Asteroid impact can produce a **mega-tsunami**, a wave that is about 100 times higher than the largest tsunami produced by an earthquake, and one that could put hundreds of millions of people at risk.[3] Fortunately, the frequency of very large asteroid impacts is very low. Of the above potential causes, tsunami produced by earthquakes are by far the most common.

FIGURE 7.6 Tsunami damage Damage from a ~3 m-high tsunami that struck Pago Pago, American Samoa, in 2009. *(Hugh Gentry/Reuters/Corbis)*

would have been saved had more people recognized from Earth's behavior that a tsunami was likely. People who felt the large earthquake would have known that a tsunami might be coming and could have evacuated to higher ground. Even thousands of miles away, where the seismic waves are not felt, there are still signals of what is about to happen. As the British schoolgirl knew, if the water suddenly recedes from the shore and exposes the sea bottom, you can expect it to come back as a tsunami wave. This is a signal to move to higher ground. People should also be informed that tsunamis are seldom one wave but are, in fact, a series of waves, with later ones many times larger and more damaging than earlier ones. The education of people close to where a tsunami may originate is particularly important, as waves may arrive 10 to 15 minutes following an earthquake. Geologists have warned that it is likely that another large tsunami will be generated by earthquakes offshore of Indonesia in the next few decades.[6,7]

Since 2006, an ocean-bottom tsunami warning system consisting of sensors that recognize tsunami waves has been in place in the Indian Ocean. In addition, much more has been done to educate people about the tsunami hazard. A tsunami in 2009, generated by a M 8.1 earthquake, struck American Samoa and other islands in the region (**Figure 7.6**). The number of lives lost was about 200, and this was fewer than might have occurred without the program of tsunami awareness and education, along with oral history of indigenous people. People got the word out about the tsunami hazard and what to look for, and that resulted in evacuations that saved lives. However, with even more education and improved warning linked to evacuation processes, more lives could have been saved.[8]

Damaging tsunami in historic time have been relatively frequent and mostly in the Pacific Basin. Recent examples include the following:[9,10]

- The 1755 (~M 9) Lisbon, Portugal earthquake produced a tsunami that, along with the earthquake and resulting fire, killed an estimated 20,000 people. Tsunami waves crossed the Atlantic Ocean and amplified to heights of 7 m (23 ft) or more in the West Indies.[9]
- The 1883 violent explosion of the Krakatoa volcano in the Sundra Strait between Java and Sumatra caused the top of the volcano to collapse into the ocean. This sudden collapse produced a giant tsunami over 35 m (116 ft) high that destroyed 165 villages and killed more than 36,000 people.[10]
- The 1946 (M 8.1) Aleutians (Alaska) earthquake produced a tsunami in the Hawaiian Islands that killed about 160 people.
- The 1960 (M 9.5) Chile earthquake triggered a tsunami that killed 61 people in Hawaii after traveling for 15 hours across the Pacific Ocean.

- The 1964 (M 9.2) Alaskan earthquake generated a deadly tsunami that killed about 130 people in Alaska and California.
- The 1993 (M 7.8) earthquake in the Sea of Japan caused a tsunami that killed 120 people on Okushiri Island, Japan.
- The 1998 (M 7.1) Papua New Guinea earthquake triggered a submarine landslide, which produced a tsunami that killed more than 2,100 people.
- The 2004 (M 9.1) Sumatran earthquake generated a tsunami that killed about 230,000 people.
- The 2009 (M 8.1) Samoan earthquake generated a tsunami that killed about 200 people.
- The 2010 (M 8.8) Chile earthquake that killed about 600 people generated a tsunami that killed about 20 people in coastal towns.

How Can an Earthquake Cause a Tsunami?

An earthquake can cause a tsunami by movement of the seafloor and by triggering a landslide. Seafloor movement is probably the more common of these two mechanisms. This movement occurs when the seafloor sits on a block of the Earth's crust that shifts up or down during a quake. In general, it takes a M 7.5 or greater earthquake to create enough displacement of the seafloor to generate a damaging tsunami. The upward or downward movement of the seafloor displaces the entire mass of water, from the sea bottom to the ocean surface. This starts a four-stage process that eventually leads to landfall of tsunami waves on the shore (**Figure 7.7**):

- If an earthquake rupture uplifts the seafloor, the water surface above the uplift initially forms an elongate dome parallel to the geologic fault. That dome collapses and generates a tsunami wave. Oscillations of the water surface and, in some cases, aftershocks along the fault produce additional waves. These waves radiate outward like the pattern made by a pebble thrown into a pond of water.
- In the deep ocean, the tsunami waves move very rapidly and are spaced long distances

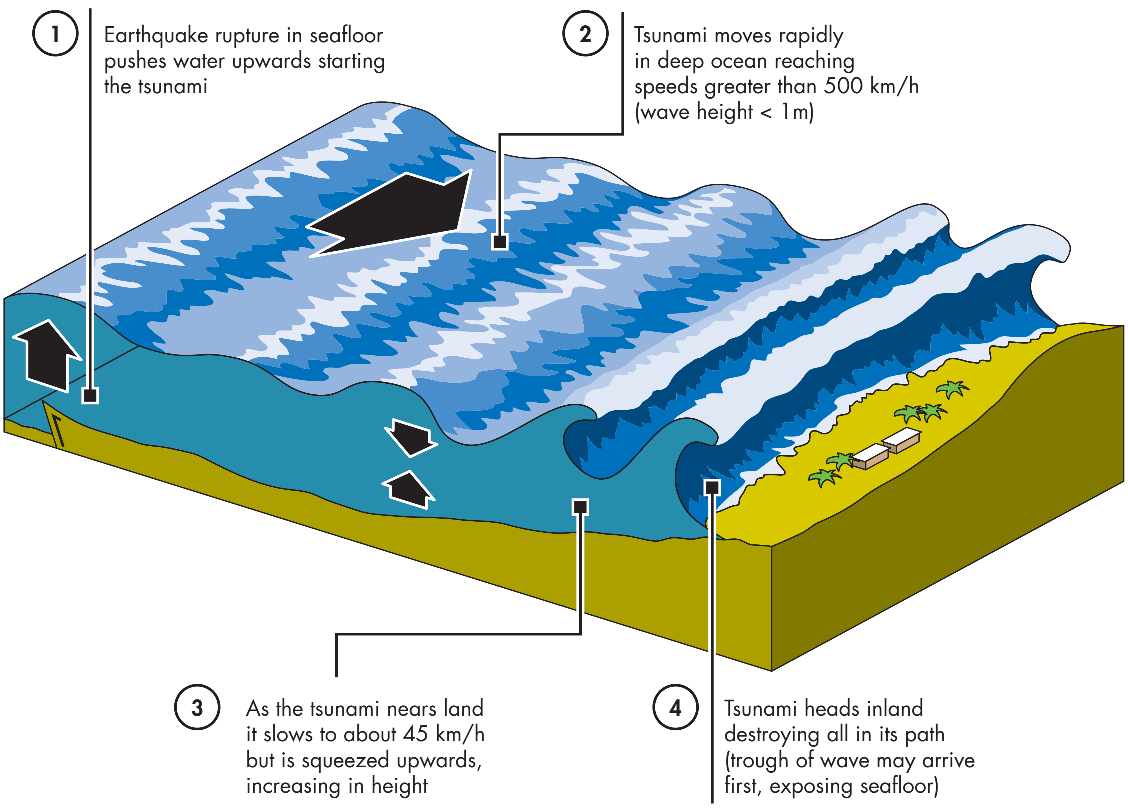


FIGURE 7.7 Tsunami damage Idealized diagram showing the process of how a tsunami is produced by an earthquake. *(Modified after the United Kingdom Hydrographic Office)*

apart. Their velocity is equal to the square root of the product of the acceleration of gravity and the water depth. The acceleration of gravity is approximately 10 m/sec^2, and the average water depth in the deep ocean is 4,000 m (13,000 ft). Thus, when we do the math, we see that, if we take the product of 10 m/sec^2 and 4,000 m and then take the square root of that number, we arrive at a velocity of 200 m/sec. Converting 200 m/sec to km/hour, we find that tsunamis travel at 720 km (450 mi) per hour, about the average airspeed for a Boeing 737 jet airliner! In the deep ocean, the spacing between the crests of tsunami waves may be more than 100 km (60 mi), and the height of the waves are generally less than 1 m (3 ft). Sailors rarely notice a passing tsunami in the deep ocean.

- As a tsunami nears land, the water depth decreases, so the velocity of the tsunami also decreases. Near land, the forward speed of a tsunami may be about 45 km (28 mi) per hour—too fast to outrun, but not nearly as fast as tsunami waves in the open ocean. This decrease in velocity also decreases the spacing between wave crests, that is, the wavelength. As the water slows down and piles up, the height of the waves increases.
- When the first tsunami wave reaches the shore and moves inland, it may be several meters to several tens of meters high and destroy nearly everything in its path. Sometimes, the trough of the wave may arrive first, and this exposes the seafloor. When tsunamis strike the coast, they generally do not come in as a giant breaking wave, as you might see on the surfing beaches of the north shore of Oahu or the California coast. Instead, when the wave arrives, it is more like a very strong and fast-rising rise in sea level. On the rare occasions when tsunamis do break, they may appear as a vertical wall of turbulent water. The movement of a tsunami inland is called the **runup** of the wave. Runup refers to the furthest horizontal and vertical distance that the largest wave of a tsunami moves inland. Once a wave has moved to its furthest extent inland, most of the water then returns back to the open ocean in a strong and often turbulent flow. A tsunami can also generate other types of waves, known as *edge waves*, that travel back and forth, parallel to the shore. The interaction between edge waves and additional incoming tsunami waves can be complex. As result of this interaction, wave amplification may occur, causing the second or third tsunami wave to be even larger than the first. Most commonly, a series of tsunami waves will strike a particular coast over a period of several hours.[11]

When an earthquake uplifts the seafloor close to land, both distant and local tsunamis may be produced (**Figure 7.8**). The initial fault displacement and uplift lift the water above mean sea level. This uplift creates potential energy that drives the horizontal movement of the waves. The uplifted dome of water commonly splits into two. One wave,

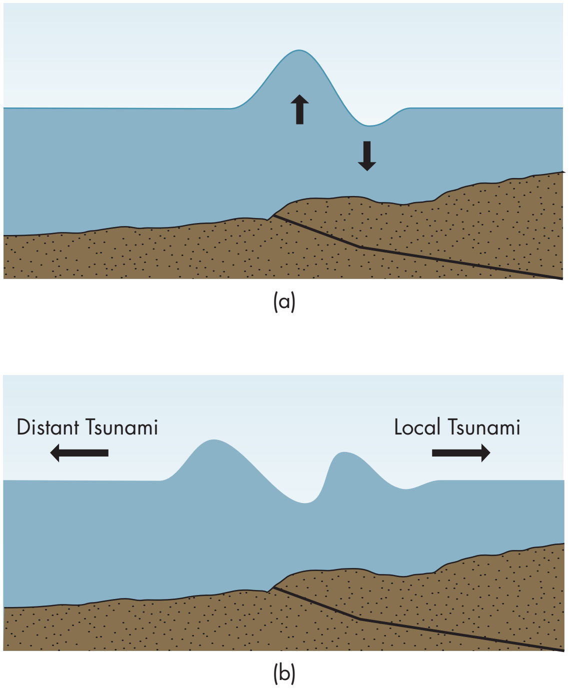


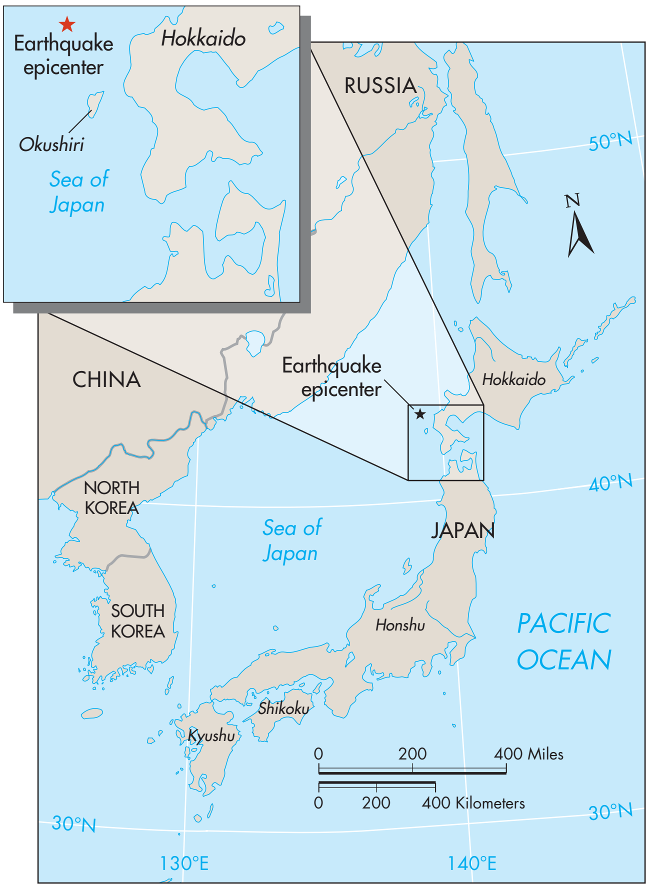
FIGURE 7.8 Distant and local tsunami (a) Fault displacement lifts the water above mean sea level, which creates potential energy that drives the horizontal propagation of the waves. In these diagrams, wave height is greatly exaggerated compared to the depth of the water. Actual height of the waves is at most a meter or so, but it is spread out to tens or several hundreds of kilometers in length. (b) The initial wave is split into a tsunami that travels out across the deep ocean (distant tsunami) and another tsunami that travels toward nearby land (local tsunami). The wave heights are also split, and each (distant and local) tsunami has a height about one-half the original wave in (a). *(Modified after U.S. Geological Survey; http://walrus.wr.usgs.gov/tsunami/basics.html)*

known as a **distant tsunami**, travels out across the deep ocean at high speed. Distant tsunamis can travel thousands of kilometers across the ocean to strike remote shorelines with very little loss of energy. The second wave, known as the **local tsunami**, heads in the opposite direction toward the nearby land. A local tsunami can arrive quickly following an earthquake, giving coastal residents and visitors little warning time. When the initial tsunami wave is split, each (distant and local) tsunami has a wave height about one-half of that of the original dome of water.[11]

An example of a local tsunami comes from the island of Okushiri in western Japan (**Figure 7.9**). On July 12, 1993, a M 7.8 earthquake in the Sea of Japan produced a local tsunami that extensively damaged Anoae, a small town on the southern tip of the island. The town was struck several times by 15 to 30 m (50 to 100 ft) waves coming around both sides of the island. There was virtually no warning because the earthquake epicenter was very close to the island (Figure 7.9). The huge waves arrived only 2 to 5 minutes after the earthquake, killing 120 people and causing $600 million in property damage.[12]

How Can a Landslide Cause a Tsunami?

Although most large tsunami are produced by fault rupture along subduction zones at tectonic plate boundaries, landslides have also generated very large tsunami. These landslides can take place underwater, where they are referred to as *submarine landslides*, or they can be large rock avalanches that fall from mountains into the sea. In most cases, the landslides are triggered by an earthquake. For example, in 1998, a M 7.1 earthquake occurred off the north shore of the island of New Guinea. The earthquake was felt at Sissano Lagoon, and shortly thereafter a tsunami arrived with little warning. In less than an hour, coastal villages were swept away, leaving 12,000 people homeless and more than 2,000 dead. The tsunami waves, which reached heights of



(a)

(b)

FIGURE 7.9 Earthquake-produced local tsunami
(a) Location of the 1993 Hokkaido-Nanse-Oki earthquake (M 7.8). *(From Hokkaido Tsunami Survey Group. 1993. Tsunami devastates Japanese coastal region.* EOS, Transactions of the American Geophysical Union *74(37):417, 432)* (b) Aerial view of the town of Anoae at the southern tip of Okushiri Island, Japan, following inundation by a local tsunami from the 1993 earthquake. Note the extensive damage to the shoreline area and fires burning from leaking propane and kerosene used for heating. *(Sankei Shimbun/Corbis/Sygma)*

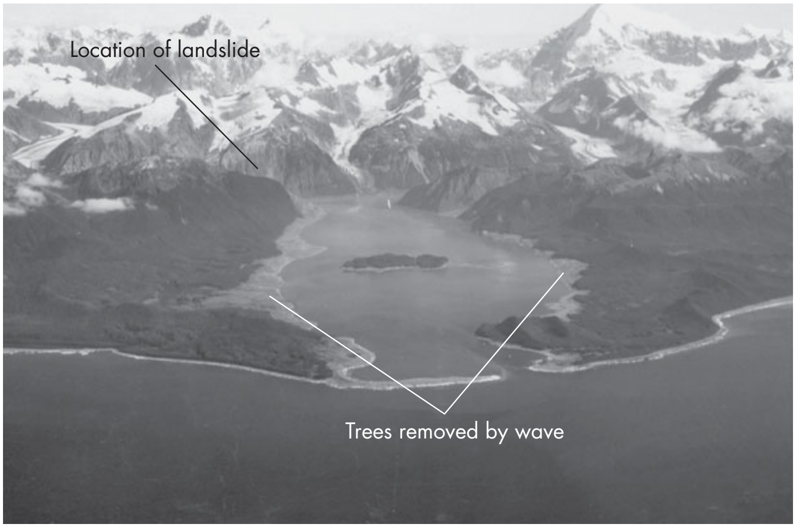


FIGURE 7.10 Landslide-produced giant wave Lituya Bay, Alaska, following a local tsunami. Exposed shoreline of the bay was produced as trees were removed by the erosive force of the wave. *(DJ Miller/USGS)*

15 m (50 ft), appear to have resulted primarily from a submarine landslide triggered by the earthquake.[13] The epicenter of the earthquake was only about 50 km (30 mi) offshore, so there was little, if any, warning time for coastal residents. This event emphasized the potentially devastating damage that can occur from a large tsunami produced by a nearby earthquake and submarine landslide.[10,13] The earthquake itself would probably not have generated a large tsunami, but it was combined with a landslide that displaced water at the bottom of the sea.

Perhaps the most famous landslide-induced giant wave occurred at Lituya Bay, Alaska, in 1958. The landslide was set in motion by a M 7.7 earthquake on a nearby fault. Approximately 30.5 million m^3 of rock fell from a cliff into the bay, instantly displacing a huge volume of seawater.[9] That volume of Earth material would fill the National Mall in Washington, DC, to a height of about 25 m (80 ft) (the height of the Hirshhorn Museum on the Mall). The huge mass of broken rock caused waters in the bay to surge upward to an elevation of about 524 m (1,720 ft) above the normal water level.[9] This splash of water was so tall that it would have washed over the Sears Tower in Chicago with 82 m (270 ft) to spare! Although the wave that swept out of the bay into the ocean wasn't nearly as large, it did pick up a fishing boat with two people onboard. The boat's captain estimated that the tsunami wave was 30 m (100 ft) high when it lifted the boat over the sand spit at the mouth of the bay. Two other fishing boats in the bay disappeared after being caught in the wave.[14] A panoramic view of the bay taken a few days after the tsunami shows that the erosive force of the wave stripped the shoreline bare of trees (**Figure 7.10**). In the area beyond the direct splash effect of the fallen rock, the high water line above the barren shoreline indicates that the local tsunami had a runup height of 20 to 70 m (65 to 230 ft).[9]

7.2 Regions at Risk

Although all ocean and some lake shorelines are at risk for tsunamis, some coasts are more at risk than others. The heightened risk comes from the geographic location of a coast in relation to potential tsunami sources, such as earthquakes, landslides, and volcanoes. Coasts in proximity to a major subduction zone, or directly across the ocean basin from a major subduction zone, are at greatest risk. A major subduction zone is considered one that is capable of periodically generating a great earthquake of M 9 or greater. Ruptures produced by these great earthquakes may extend for 1000 km (625 mi) or more along the subduction zone and produce significant uplift of the seafloor. The greatest tsunami hazard, with return periods of several hundred years, is adjacent to those major subduction zones with a convergence of a few centimeters per year. These include the Cascadia subduction zone in the Pacific Northwest, the Chilean trench along southwestern South America, and the subduction zones off the coast of Japan.[15]

Tsunami can range in height from a few centimeters to 30 m (100 ft) or more. Those that have a runup height of at least 5 m (16 ft) are considered significant tsunamis and are commonly produced by high-magnitude earthquakes and associated submarine slides. A recent assessment of global tsunami hazard ranks the hazard from relatively low to greatest based upon the return period of a significant tsunami (at least 5 m runup) (**Figure 7.11**). Keep in mind that this map is highly generalized because runup from tsunami varies considerably with the shape of the seafloor immediately offshore and with the type of topography and vegetation landward of the beach. Both the offshore and shoreline topography can greatly accentuate tsunami wave height. Also, not enough is known about global seismicity to accurately predict return periods of earthquakes with M 9 or above—those quakes that are most likely to produce a significant tsunami. Examination of the map reveals that most zones of greatest hazard surround the Pacific Ocean. This is no surprise, given that most of the major subduction zones are found on the margins of the Pacific. Other regions judged to have the greatest hazard are parts of the Mediterranean, as well as the northeastern side of the Indian Ocean. The good news about the risk from significant tsunami is that almost all of them will cause only substantial damage within a couple hundred kilometers from their source. However, the very largest subduction zone earthquakes may cause substantial damage several thousands of kilometers from the source. That certainly was the case with the 2004 Indonesian tsunami that raced across the Indian Ocean, causing death and destruction as far away as the east coast of Africa. However, most of the death and destruction were much closer to the earthquake epicenter (Figure 7.3).

An interesting example of damage from a distant earthquake comes from 3 centuries ago. In the year 1700, a tsunami generated by an estimated M 9 earthquake on the Cascadia subduction zone reached the shores of Japan approximately 12 hours later (**Figure 7.12**). You might wonder how we are able to determine the magnitude of the earthquake and determine that it created a tsunami in Japan. This discovery started with geologic investigations in North America that found logs and soil that were buried below a tsunami deposit sometime after 1660. The logs and other plant material in the soil were radiocarbon dated to determine the time that they were

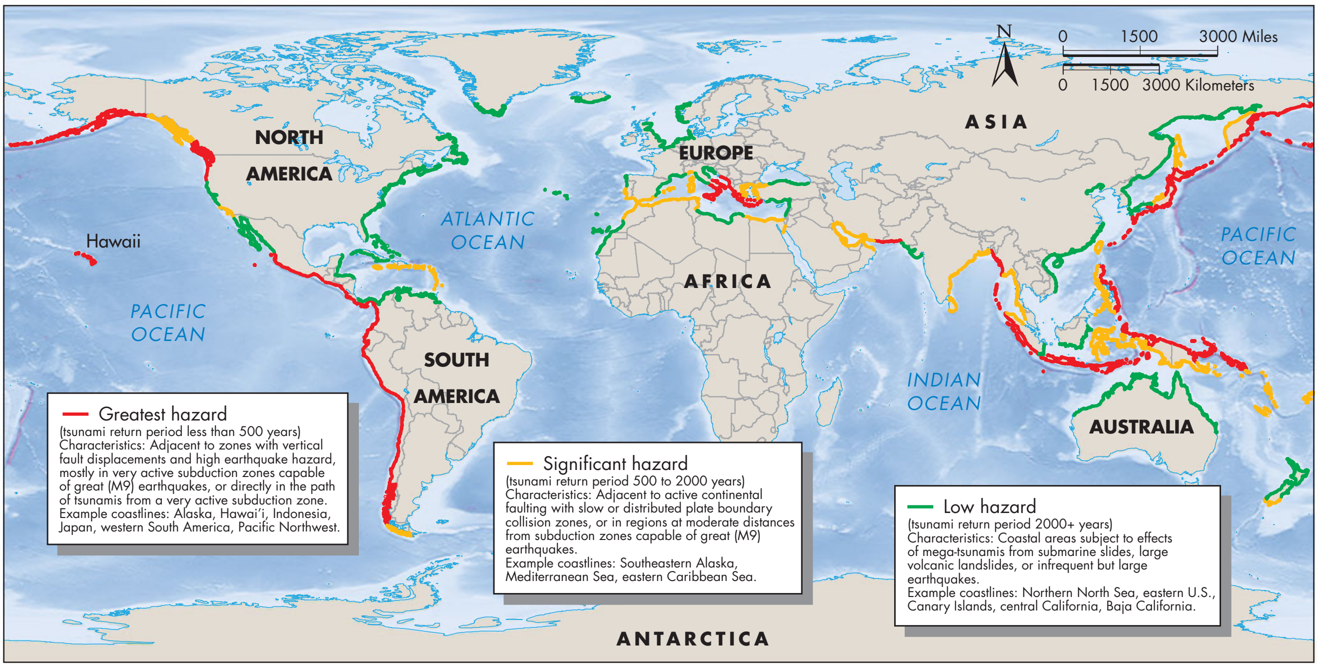


FIGURE 7.11 Global tsunami hazard Map of the relative hazard of coastlines to experience a tsunami that is at least 5 m (16 ft) high. *(Modified from Risk Management Solutions. 2006.* 2004 Indian Ocean Tsunami report. *Newark, CA: Risk Management Solutions, Inc.)*

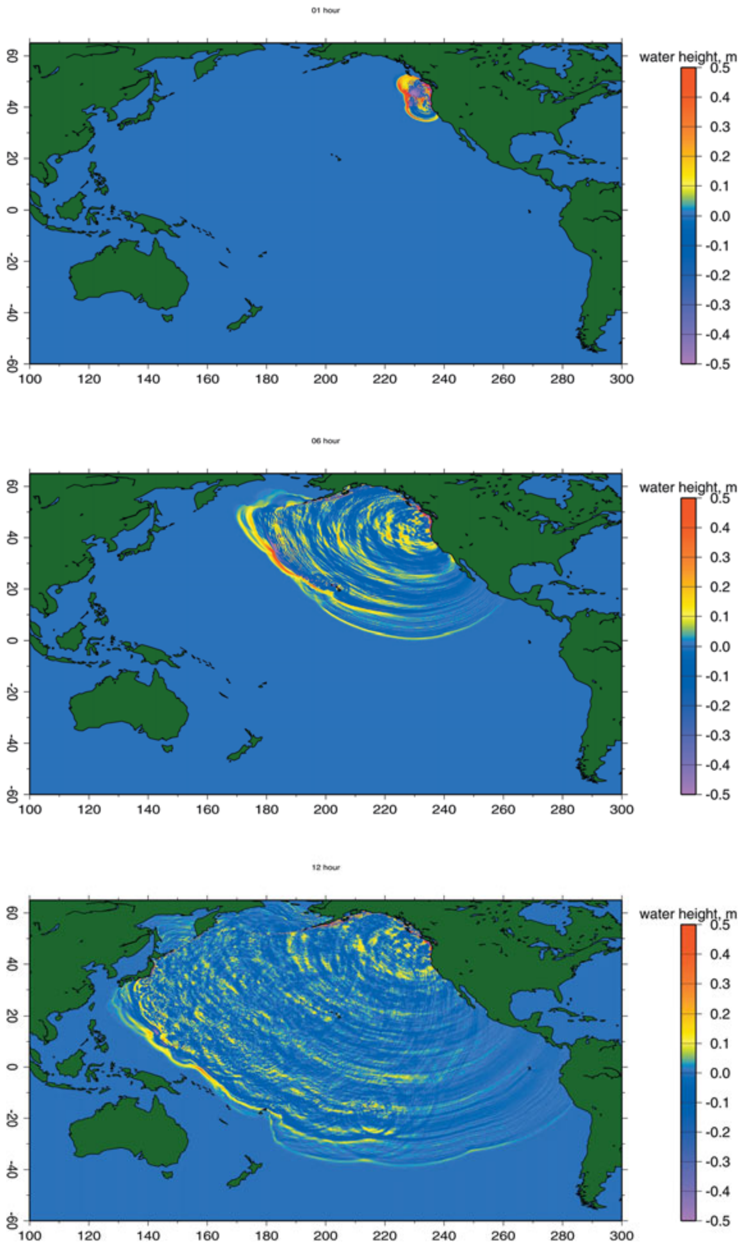


FIGURE 7.12 Tsunami of 1700 This output from a computer model of the January 1700 tsunami is based on arrival times at several sites in Japan. The maps show wave height and location 1 hour, 6 hours, and 12 hours after a ~M 9 earthquake occurred on the Cascadia subduction zone. Such an earthquake would produce a fault displacement of around 19 m (60 ft) over a distance of about 1,100 km (680 mi) from British Columbia south to northern California. *(Courtesy of Kenji Satake)*

last alive, and the deposits showed evidence of subsidence at the time of the earthquake. Based upon the geologic evidence, the length of rupture was estimated to be about 1,000 km (620 mi).[16–18] The evidence from Japan consists of historical descriptions of a tsunami with a 1 to 5 m runup height that took place in 1700. Knowing the time of arrival of the tsunami in Japan, scientists have inferred that the tsunami originated at the Cascadia subduction zone about 9:00 P.M. PST on January 26, 1700.[16]

7.3 Effects of Tsunamis and Linkages to Other Natural Hazards

The effects of tsunami are both primary and secondary. Primary effects are related to the inundation of the water and resulting flooding and erosion. Virtually nothing can stand in the path of a truly high-magnitude tsunami. The wave energy is sufficient to tear up beaches and most coastal vegetation, as well as homes and buildings in its path. These effects diminish with distance from the coast. Much of the damage to both the landscape and human structures results from the tremendous amount of debris carried by the water as it moves inland and then back again to the ocean. What is left behind is often bare, eroded ground and areas covered with all sorts of human and natural debris (**Figure 7.13**).

Secondary effects of tsunami occur in the minutes, hours, days, and weeks following the event. Immediately following a tsunami, fires may start in urban areas from ruptured natural gas lines or from the ignition of flammable chemicals that were released from damaged tanks. Water supplies may become polluted from floodwaters, damaged wastewater treatment systems, and rotting animal carcasses and plants. Disease outbreaks may occur, as people surviving the tsunami come in contact with polluted water and soil. In the 2004 Indonesian tsunami, public health officials were initially concerned that there would be outbreaks of waterborne illnesses, such as malaria and cholera. Fortunately, this did not become a serious problem because of the quick action of relief agencies and the destruction of mosquito breeding grounds by saltwater

(a)

(b)

FIGURE 7.13 Damage and debris from 2004 Indonesian tsunami (a) In some areas, the tsunami removed all but the most sturdy buildings, such as this mosque in Aceh Province, Indonesia. *(Spencer Platt/Getty Images)* (b) In other areas, such as this part of the Indonesian resort town of Pangandaran, the tsunami piled up huge amounts of human and natural debris. This made it difficult for these soldiers to locate victims. *(Dimas Ardian/Getty Images)*

flooding. What did occur is a pneumonia-like disease known as "tsunami lung," a condition that developed in people who inhaled bacteria in muddy saltwater. Because the disease was not initially recognized and there were few antibiotics or medical personnel available for treatment, many of the patients developed advanced lung infections that resulted in paralysis. Fortunately, treatment with antibiotics eventually brought the infections under control.[19]

There are several linkages between tsunami and other natural hazards. Tsunami are obviously closely linked to submarine and coastal earthquakes and landslides, as well as island volcanic explosions and oceanic impacts of asteroids and comets. For earthquake-generated tsunamis, coastal communities near the epicenter experience casualties and property damage from both the ground shaking of the earthquake and inundation by the tsunami. Powerful tsunami waves interact with coastal processes to change the coastline through erosion and deposition of sediment. There was dramatic evidence of this interaction following the 2004 tsunami in the area near Banda Aceh, Indonesia (Figure 7.4). A combination of erosion caused by the tsunami and subsidence caused by the earthquake has altered the coastal area to the point that it scarcely resembles what it was prior to the event.

7.4 Minimizing the Tsunami Hazard

The magnitude and frequency of tsunami are not in any way tied to human activity. As with hurricanes, people who move to coasts that have an elevated risk for tsunami are increasing the likelihood that they will be affected by this natural process. The rapid development of coastal areas in recent decades for a variety of land uses, along with increase in human population of coastal cities in many regions, has increased the hazard. Seattle, Washington, with a significant tsunami hazard, had a population of about 43,000 in 1890. Today, the metropolitan area has a population of nearly 100 times that (over 4 million).

There are some lessons to be learned from past tsunami that can be applied to reduce the damage from future events. For example, we can plant buffer zones of trees along a coast that will absorb some of the impact of incoming tsunami waves. We might also consider the strength of our buildings to withstand the onslaught of moderate tsunamis and move other structures inland where they are less likely to be damaged. Loss of life is reduced by warning and evacuation.

A number of strategies are available for minimizing the tsunami hazard, including the following:

- Detection and warning
- Structural control

- Construction of tsunami runup maps
- Land-use planning
- Probability analysis
- Education
- Tsunami-ready status

Detection and Warning

Since nearly all large tsunami are associated with giant earthquakes, our first warning comes from an earthquake in an offshore area that is large enough to produce a tsunami. For distant tsunami, we have the capability to detect them in the open ocean and accurately estimate their arrival time to within a few minutes. This information has been used to create a successful tsunami warning system in the Pacific Ocean.

A tsunami warning system has three components: a network of seismographs to accurately locate and determine the depth and magnitude of submarine and coastal earthquakes, automated tidal gauges to measure unusual rises and falls of sea level, and a network of sensors connected to floating buoys (**Figure 7.14**). Surface buoys with a bottom sensor, known as a *tsunameter*, detect small changes in the pressure exerted by the increased volume of water as a tsunami passes overhead (Figure 7.14a). This information is relayed by satellite to a warning center and is combined with tidal gauge information to predict tsunami arrival times. For example, an underwater earthquake in Hawaii could produce a tsunami that would radiate outward across the entire Pacific Ocean and arrive at different times in California, Alaska, Japan, and Papua New Guinea (Figure 7.14b). Following the Indonesian tsunami, similar systems are being created in the Indian and Atlantic Oceans, including warning sensors for Puerto Rico and the east coast of the United States and Canada.

For a local tsunami that strikes land very close to the source of the earthquake, there may be very little warning time. People close to the source, though, will probably feel the earthquake and can immediately move inland to higher ground. Certainly, the water receding is a sign to run inland. Some coastal communities in Hawaii, Alaska, the Pacific Northwest, British Columbia, Japan, and elsewhere also have warning sirens to alert people that a tsunami may soon arrive.

Structural Control

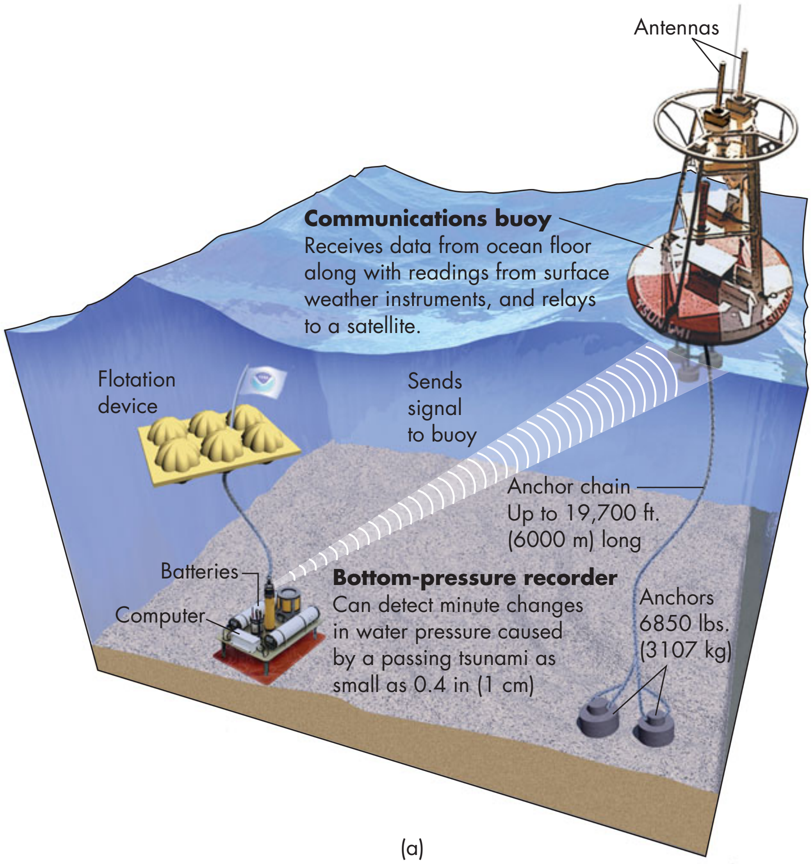
Tsunami that are even 1 or 2 m high have such power that many houses and small buildings are unable to withstand their impact.[9] However, building designs for larger structures, such as high-rise hotels and critical facilities, can be engineered in such a way as to greatly reduce or minimize the destructive effects of a tsunami. For example, the city of Honolulu, Hawaii, has special requirements for construction of buildings in areas with a tsunami hazard. However, for most hazard areas, the current building codes and guidelines do not adequately address the effect of a tsunami on buildings and other structures.[20]

Tsunami Runup Maps

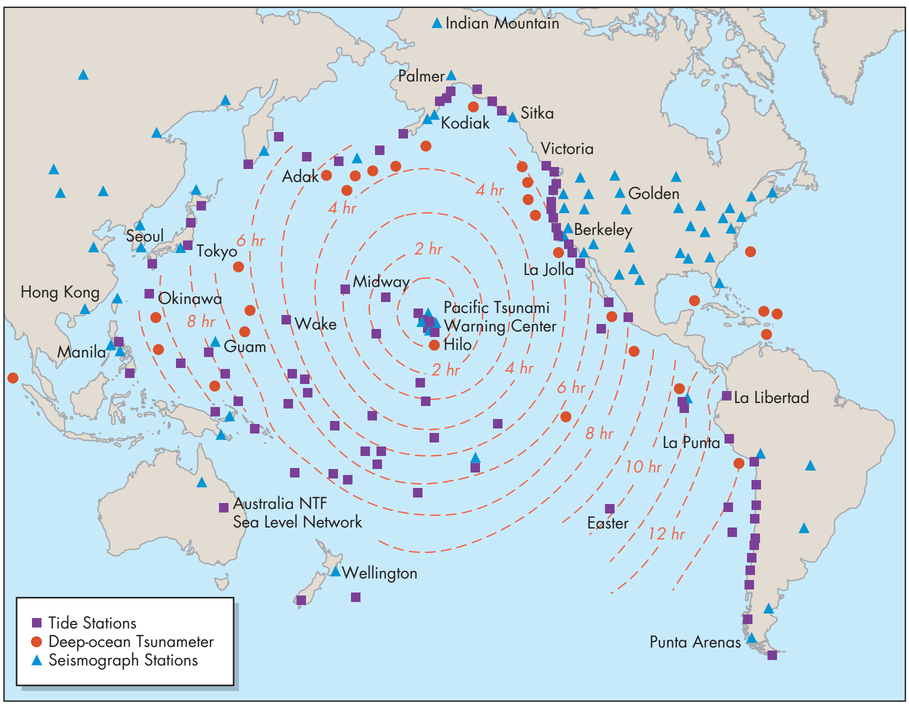
Following a tsunami, it is a fairly straightforward procedure to produce a **tsunami runup map** that shows the level to which the water traveled inland. Such a map was created for the island of Oahu, Hawaii, following the 1946 tsunami that originated from an earthquake in Alaska's Aleutian Islands (**Figure 7.15**, page 239). That map illustrates the tremendous variability of runup height from a typical tsunami. The runup from the 1946 tsunami varied from about 0.6 m (2 ft) in Honolulu to 11 m (36 ft) at Kena Point and Makapuu Point on opposite ends of the island.

Before a tsunami strikes, a community can produce a hazard map that shows the area that is likely to be inundated by a given height. Huntington Beach, California, one of a number of American and Canadian communities that have a significant tsunami hazard, has prepared such a map (**Figure 7.16**, page 240). Although the probability of a large tsunami in southern California is relatively low, the consequences of such an event could be catastrophic. For example, the entire city of Huntington Beach has an elevation of less than 33 m (100 ft), and three-quarters of the city is less than 8 m (25 ft) above sea level. Huntington Beach itself faces to the southwest and, as such, is vulnerable to a tsunami from either the south or west. Such an event, for example, might originate in Alaska, Japan, or the South Pacific. The beach attracts up to 100,000 people or more each day during the summer, and the city is giving serious consideration to the possibility of a tsunami. Many other cities and areas have produced tsunami runup maps, and this trend will undoubtedly continue in the future.

FIGURE 7.14 Tsunami warning system (a) A surface buoy and bottom sensor to detect a tsunami. (b) Travel time (each band is 1 hour) for a tsunami generated in Hawaii. The wave arrives in Los Angeles in about 5 hours. It takes about 12 hours for the waves to reach South America. Locations of 30 DART tsunameter buoys are shown with red dots. At least 14 additional DART tsunameter buoys are planned for the Pacific and Atlantic Oceans. *(NOAA)*



(a)



(b)

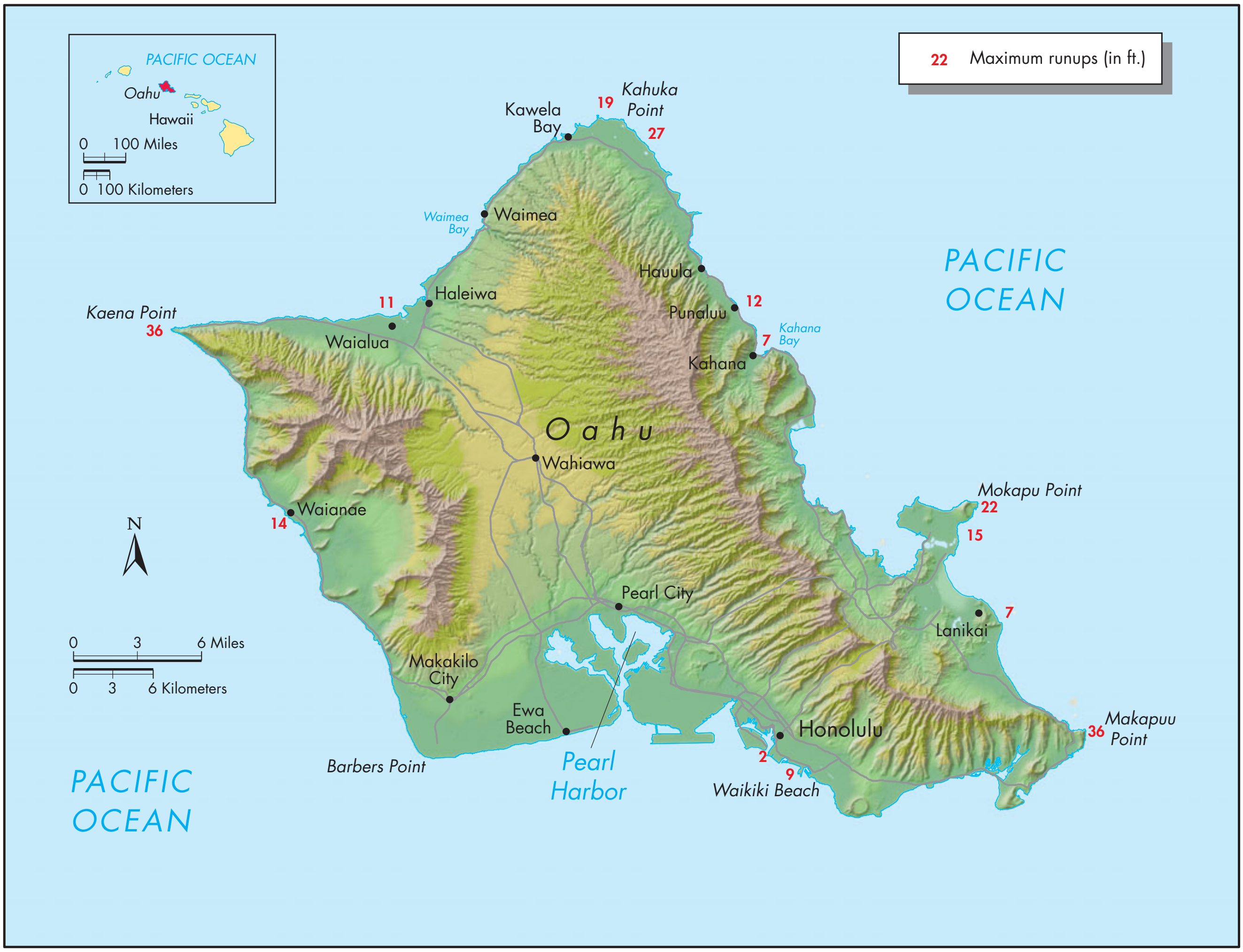


FIGURE 7.15 Tsunami runup on Oahu, Hawaii Map of Oahu, Hawaii, showing runup of the 1946 tsunami that originated from an earthquake in the Aleutian Islands, Alaska. Maximum runups are indicated in feet. *(Modified after Walker, D. 1994.* Tsunami Facts. *SOEST Technical Report 94-03. School of Ocean and Earth Science and Technology)*

Land Use Planning

In the aftermath of the 2004 Indonesian tsunami, scientists discovered that tropical ecology played a role in determining tsunami damage. Where the largest waves struck the shore, there was inevitably massive destruction (**Figure 7.17**, page 241). In other areas, the damage was not uniform. Some coastal villages were destroyed, while others were less damaged. Those villages that were spared destruction were partly protected from the energy of the tsunami by either a coastal mangrove forest or several rows of plantation trees that reduced the velocity of incoming water.[21] Coastal land use and land cover studies have documented the advantage of locating villages inland behind a coastal forest (**Figure 7.18**, page 242). It has been suggested that, where the forest grows naturally, there may be places somewhat protected from wave attack by the near-shore and land topography. Thus, development in areas with a tsunami hazard might look to land use planning that includes identifying where serious tsunami damage has occurred in the past and avoiding the most hazardous places. That is an example of using the principle of uniformitarianism discussed in Chapter 1.

With rapid coastal development for a variety of purposes, including tourism, coastal mangroves are often removed and replaced by homes, high-rise hotels, and other buildings. These structures are often located very close to the beach and, thus, are vulnerable to tsunami attack. While it may not

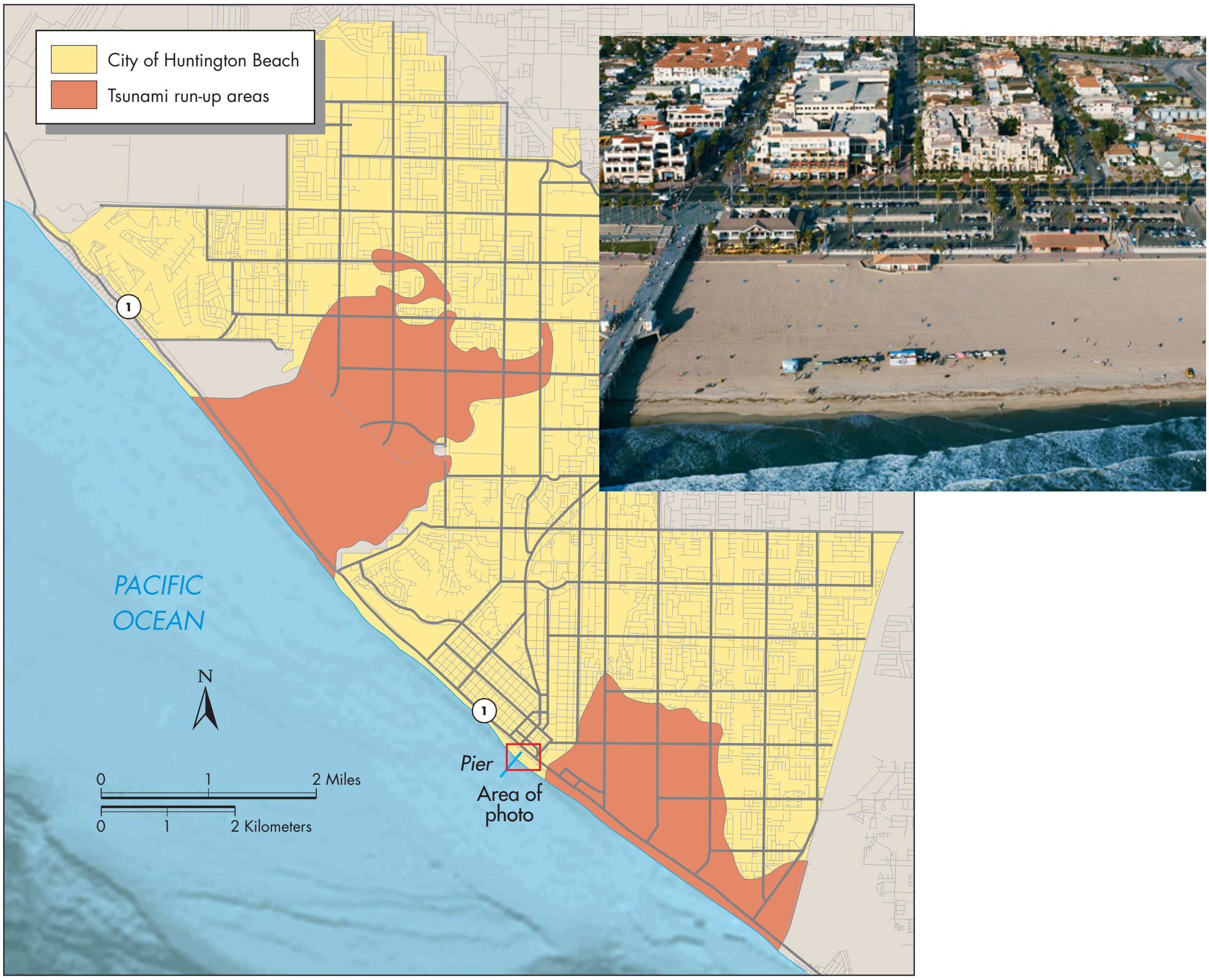


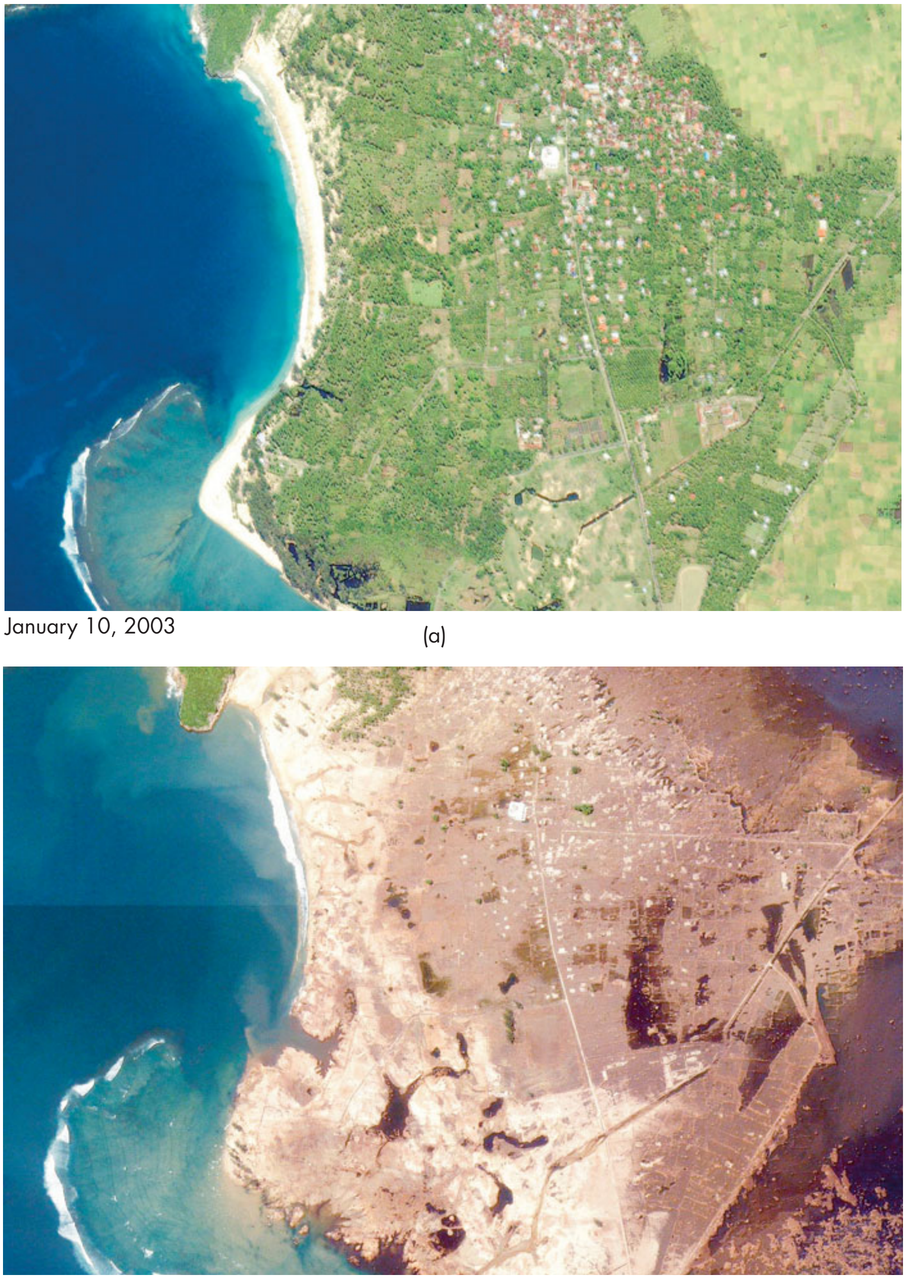
FIGURE 7.16 Huntington Beach, California, tsunami runup map (a) Map showing areas likely to be inundated by tsunami runup in red. *(Courtesy City of Huntington Beach)* (b) The popular beach, with pier and area to the southeast. *(© 2002–2006 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org)*

be practical to move tourist areas inland, planting or retaining native vegetation could provide a partial buffer from a small to moderate tsunami attack. However, large tsunami waves can erode large trees from the soil, and their trunks and branches can then move inland with the water, producing a serious hazard to people and structures. The best and safest approach to lessen the tsunami hazard is quick evacuation.

Probability Analysis

The risk of a particular event may be defined as the product of the probability of that event occurring and the consequences, should it occur. Thus, determining the likelihood or probability of a tsunami is an important component in analyzing the potential hazard. For the most part, the hazard analysis for tsunami has relied upon evidence from past tsunami to determine the hazard rather than attempt to calculate the probability of a future tsunami. The more deterministic approach is simply to derive tsunami inundation maps, such as that shown in Figure 7.16 and use the maps to help develop evacuation routes. In contrast, analysis of the probability of a tsunami hazard provides information not only on the likelihood of the event, but also other aspects as well, such as location of the event, the extent of the runup, and the possible severity of damage. The approach taken in developing a probabilistic analysis of the tsunami hazard is to:

- Identify and specify the potential earthquake sources and their associated uncertainties.



January 10, 2003 (a)

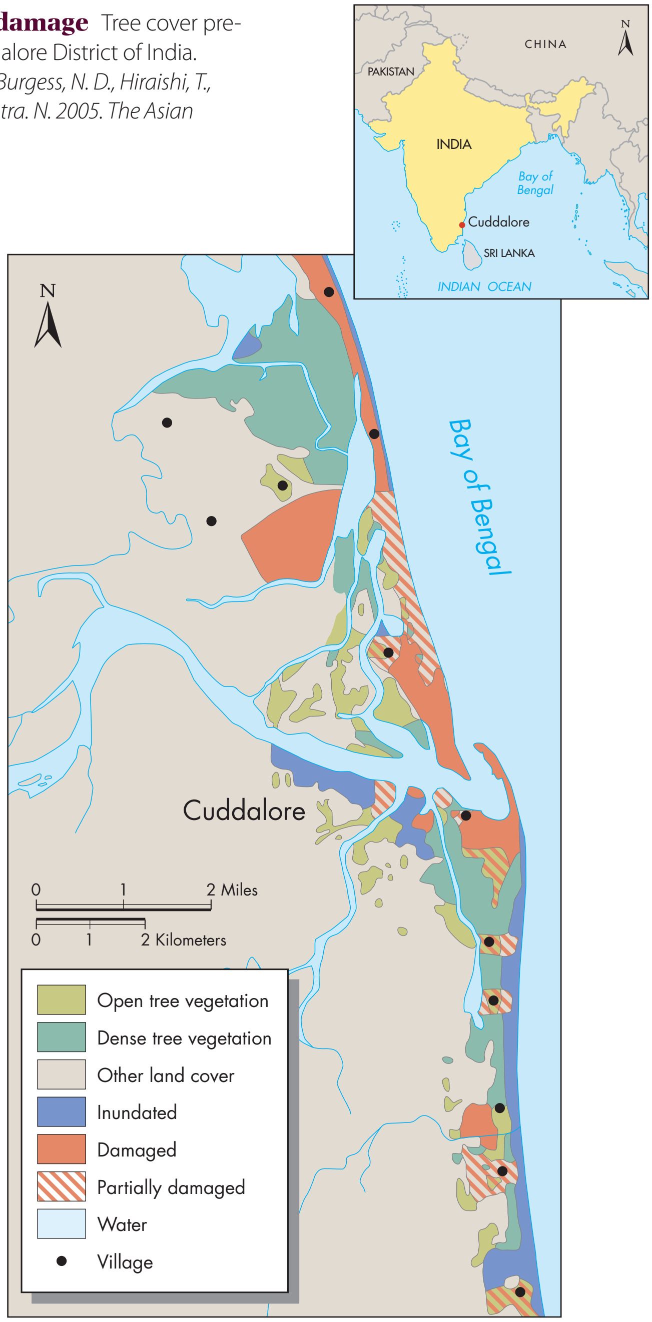
December 29, 2004 (b)

FIGURE 7.17 Tsunami damages to trees (a) Before and (b) after 2004 Indonesian tsunami removed many trees. *(IKONOS satellite images courtesy of Centre for Remote Imaging, Sensing and Processing [CRISP] and GeoEye)*

- Specify relationships that will either attenuate or reduce tsunami waves as they travel from the source area.
- Apply probabilistic analysis to the tsunami hazard similar to what is currently being done for earthquake hazard analysis. However, with tsunamis, the analysis must consider the fact that tsunami can originate from multiple sources, including ones that are far away from the location where the hazard is present.

This probabilistic approach to tsunami hazard assessment is still being developed. One difficulty is that tsunami at a particular location are generally rare events. If there was not sufficient activity in the past to develop the probability of future events, the analysis depends upon a statistical technique known as Monte Carlo simulation. This technique has been used to simulate the behavior of earthquakes and tsunami. The overall objective is to determine tsunami return periods and probabilities for both

FIGURE 7.18 Trees provide some protection from tsunami damage Tree cover pre-tsunami with post-tsunami damages to the land and villages in the Cuddalore District of India. *(Modified after Danielsen, F., Serensen, M. K., Olwig, M. F., Selvam, V., Parish, F., Burgess, N. D., Hiraishi, T., Karunagaran,V. M., Rasmussen, M. S., Hansein, L. B., Quarto, A., and Suryadiputra. N. 2005. The Asian tsunami: A protective role for coastal vegetation. Science 310:643)*



distant and local sources. To apply this technique, the Monte Carlo simulation selects a random sample of earthquakes of various magnitudes and determines the tsunami that would be propagated from these quakes. Using these tsunami, a mathematical model is then constructed to estimate the tsunami amplitude or runup along a particular coast. This must be done for each of the potential seismic sources for that particular coastline.[22]

Education

Education concerning the tsunami hazard is critical to minimizing risk. This was shown dramatically during the 2004 Indonesian tsunami, when numerous lives were saved because people recognized that the receding seawater was a warning sign of an impending tsunami. Likewise, it is important to educate coastal residents and visitors as to the difference between a **tsunami watch**, which is a notification that an earthquake that can cause a tsunami has occurred, and an actual **tsunami warning** that a tsunami has been detected and is spreading across the ocean toward their area. For a distant tsunami, there will likely be several hours before the waves arrive after a warning has been issued. In a local tsunami, there may be very little warning time, and, so, more attention must be given to nature's warning systems, such as earthquake shaking or the water receding from a shoreline. People must also be taught that tsunami come in a series of waves, and that the second and third waves may be larger than the first one. Finally, people must be told that the water returning to the ocean once a wave has runup is just as dangerous as the incoming water.

Tsunami Ready Status

In order for a community to be prepared, or **tsunami ready**, it must:

- Establish an emergency operation center with 24-hour capability
- Have ways to receive tsunami warnings from the National Weather Service, Canadian Meteorological Centre, Coast Guard, or other agencies
- Have ways to alert the public
- Develop a tsunami preparedness plan with emergency drills
- Promote a community awareness program to educate people concerning a tsunami hazard

These guidelines for tsunami-readiness status are being applied to a number of communities in California and other areas. For example, the University of California, Santa Barbara, and the city of Huntington Beach, California (Figure 7.16), have been certified as tsunami ready.

The educational component is of particular importance. Most people don't even know if a tsunami watch or warning is issued. For example, in 2005, there was an earthquake in the Pacific, far away from the city of Santa Barbara. As it turned out, a tsunami did not occur, but a tsunami watch was issued up and down the California coastline. Nothing was said about the size of the possible tsunami, and, so, some people, on hearing the notice, drove to the top of a nearby mountain pass thousands of feet above sea level. Those locations were great for views, but people certainly did not need to drive that far or that high to evacuate the potential danger zone. There was no plan in place to directly observe the tsunami, and the news media reported that some people perched on a sea cliff at night, while others climbed palm trees to see if the wave was coming. This experience in Santa Barbara, and other West Coast communities, suggests that even many "tsunami ready" communities are not adequately prepared for the tsunami that will eventually strike their coasts.

7.5 Perception and Personal Adjustment to Tsunami Hazard

The above discussion suggests that many people do not know the signs of an approaching tsunami or what to do if a watch or warning is issued. From a personal perspective, if a warning is issued, people can take the following actions:

- While all earthquakes do not cause a tsunami, they might. If you feel a strong earthquake and are at the beach, leave the beach and low-lying coastal area immediately.
- If the trough of a tsunami wave arrives first, the ocean will recede. This is one of nature's warning signs that a wave is on the way and that you should run from the beach.
- Although a tsunami may be relatively small at one location, it may be much larger nearby.
- Tsunami generally consist of a series of waves, and there can be up to an hour between waves. Therefore, stay out of dangerous areas until a notice that all is clear is given by the proper authorities.
- Coastal communities, as they gain tsunami-readiness status, will have warning sirens; if you hear a siren, move away from the beach to higher ground (at least 20 m [60 ft] above sea level) and listen for emergency information.
- If you are aware that a tsunami watch or warning has been issued, do not go down to the beach to watch the tsunami. If you can actually see the wave, you are probably too close to escape. These waves look very small out at sea because of the vast distance to the horizon. Remember that these waves move fast and can be deadly. A 2 m (6 ft) tall person is very small compared to a 15 m (50 ft) tsunami wave (**Figure 7.19**).

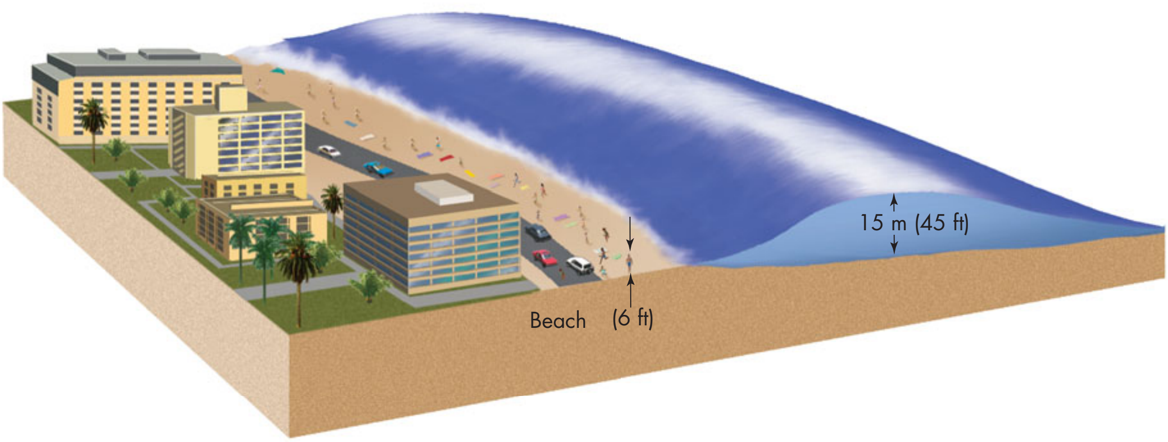


FIGURE 7.19 A person versus a tsunami Tsunami height can be huge compared to the waves we normally see on a beach. (See also Figure 4.5.)

Making The Connection

Linking the Opening Case History About the 2004 Indonesian Tsunami to the Fundamental Concepts

Consider and discuss the following questions:

1. What is the role of human population increase in impacting the Indonesian tsunami of 2004?
2. Why do you think that prior to the 2004 Indonesian tsunami, there was no warning system in the Indian Ocean? Was this a function of science or values?
3. Considering the very many islands in the Pacific and Indian Oceans, what do you think is necessary to reduce the potential tsunami hazard? In fact, is such reduction in many areas practical and cost-effective?
4. Sustainability is all about trying to ensure that future generations have fair access to the resources that Earth has to offer. Do you think that there is any strong link between sustainability and a tsunami? In other words, are coastlines sustainable with or without reducing the hazard of tsunami to coastal cities, tourist areas, and other areas of interest?

Summary

The 2004 tsunami in the Indian Ocean that claimed about 250,000 lives was an international wake-up call that we are not yet prepared for the tsunami hazard. Of primary importance is to ensure that we have a tsunami warning system available in the world's major ocean basins. This warning system must be designed to reach both coastal residents and visitors. The system must be coupled with an effective education program, so that people are more aware of the hazard.

A tsunami is produced by the sudden vertical displacement of ocean water. Several possible processes can produce tsunami, including underwater landslides, submarine volcanic explosions, and impact of extraterrestrial objects. However, the major source of large damaging tsunami over the past few millennia has been giant earthquakes associated with the major subduction zones on Earth. These tsunami have formed where geologic faulting ruptures the seafloor and displaces the overlying water. When this happens, both a distant and local tsunami may be produced. Distant tsunami can travel thousands of kilometers across the ocean to strike a remote shoreline. On the other hand, a local tsunami heads toward a nearby coast and can strike with little advance warning.

Effects of a tsunami are both primary and secondary. The primary effects are related to the powerful water from the tsunami runup that results in flooding and erosion. Virtually nothing can stand in the path of a high-magnitude tsunami. In 2004 in Indonesia, huge concrete barriers were moved by the force of the waves. Secondary effects of a tsunami include a potential for water pollution, fires in urban areas, and disease to people surviving the event.

Tsunami are linked to other natural hazards. For example, they are obviously tightly linked to the earthquakes that cause them, and, thus, their effects are often combined with the ground shaking, fires, and subsidence associated with the quakes. Tsunami waves also interact with coastal processes to change the coast line through erosion and deposition of sediment. Following an earthquake and tsunami, a coastal area may scarcely resemble what it was prior to the event.

A number of strategies are available to minimize the tsunami hazard. These include detection and warning, structural control, construction of tsunami runup maps, land use practices, probability analysis, education, and achieving tsunami-ready status. Of these, the detection and warning system is of paramount importance. For distant tsunami, we have the capability to detect them in open ocean and accurately estimate their arrival time to within a few minutes. For local tsunami, it is more difficult to provide adequate warning, as tsunami wave formation quickly follows an earthquake or earthquake-produced landslide. In this case, warning sirens can alert people that a tsunami may soon arrive.

Without adequate education, watches and warnings are often ineffective because many people do not know how to recognize a tsunami or take appropriate action to save themselves and others. Through education, people can learn the natural warning signs of an approaching tsunami. This may include the earthquake shaking itself and withdrawal of seawater prior to arrival of the large wave. People must understand that tsunami come in a series of waves, and that the second or third wave may be the largest. In addition, the water returning to the ocean following tsunami inundation can cause as much damage as the runup of the incoming waves.

Along coasts with great or significant tsunami hazard, most communities have not adequately prepared for this underestimated natural hazard. Adequate preparation includes improved perception of the hazard, development of ways to alert the public, preparation and implementation of a tsunami preparedness plan, and promotion of community awareness and education concerning the hazard.

Revisiting Fundamental Concepts

Human Population Growth
Some of the fastest-growing cities and tourist areas on Earth are in the coastal zone. Often, these areas face a tsunami hazard. As human population continues to grow and more people move to coastal areas, it seems inevitable that the amount of damage done by a tsunami will increase.

Sustainability Tsunami are natural processes that have affected coastlines throughout geologic history. Sustaining coastlines in natural areas is fairly straightforward, but provisions in areas with a tsunami hazard should include warning systems so that people living in the coastal zone may evacuate prior to arrival of tsunami waves.

Earth as a System Tsunami are related to Earth systems in a variety of complex ways. First, tsunami inundate the land with seawater, sediment, and debris, and, so, tsunami deposits may be incorporated within the rock record. Investigations of areas where periodic tsunami have occurred often involve the study of sediment that has been deposited by a tsunami and linking this sediment to a chronology to understand how often these events have happened in the past. Thus, the tsunami record is part of Earth System Science, which has the objective of understanding Earth processes on a time scale of importance to people.

Hazardous Earth Processes, Risk Assessment, and Perception Tsunami have the potential to produce catastrophes and cause extensive damage to property and loss of life. Risk assessment is fairly straightforward and involves the identification of the probability of a tsunami occurring in a particular area times the consequences when such an event actually occurs. Minimization of the risk of a tsunami is based primarily on warning systems that a tsunami is likely to strike a particular coast at a specific time and evacuation. A variety of land use choices are available that can help minimize damages to human systems, such as buildings.

Scientific Knowledge and Values Scientific studies of tsunami have advanced to the point that we understand what cause tsunami, at least those generated by earthquakes and landslides. Values enter into the tsunami story in terms of how we spend limited resources to provide better warning of tsunami and how warnings are provided to people living in coastal areas. It is not uncommon on the western coast of the United States in Oregon and the Hawaiian islands to have a system of sirens that warn people in the coastal zone if a tsunami warning is issued. The purpose is to advise people to evacuate low-lying areas. Expansion of tsunami warning sirens and other methods of alerting people to the tsunami hazard are dependent upon expenditure of sufficient funds to meet those objectives. Our willingness to spend this money in more areas will be a function of our value system, particularly in areas of the world where local funds may not be sufficient to provide a warning system.

Key Terms

distant tsunami (p. 232)
local tsunami (p. 232)
mega-tsunami (p. 228)
runup (p. 231)
tsunami (p. 228)
tsunami ready (p. 242)
tsunami runup map (p. 237)
tsunami warning (p. 242)
tsunami watch (p. 242)

Review Questions

1. What is a tsunami?
2. How do natural processes cause a tsunami? What is the primary process?
3. What is the difference between a distant tsunami and local tsunami?
4. What are the major effects of a tsunami?
5. Explain the relationship between plate tectonics and tsunami.
6. How are tsunami detected in the open ocean?
7. What is the difference between a tsunami watch and a tsunami warning?
8. What are the primary and secondary effects of tsunami?
9. Describe the methods used to minimize the tsunami hazard.
10. What is meant by tsunami-ready status?

Critical Thinking Questions

1. You are charged with developing an education program with the objective of raising a community's understanding of tsunami. What sort of program would you develop, and what would it be based upon?
2. What do you think the role of the media should be in helping to make people more aware of the tsunami hazard? How should scientists be involved in increasing the perception of this hazard?
3. You live on a coastal area that is subject to large, but infrequent, tsunami. You are working with the planning department of the community to develop tsunami-ready status. What issues do you think are most important in obtaining this status, and how could you convince the community that it is necessary or in the community's best interest to develop tsunami-ready status?
4. How might we better educate people about the tsunami hazard?
5. Why might it be difficult for people who live far from a serious earthquake hazard to appreciate and prepare for tsunami damage?
6. What would be the potential economic gains and losses of large scale planting of trees to provide a buffer from tsunami?

Companion Website

www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Harry Glicken at Mount St. Helens Observation site in 1980, before the eruption that blew the top off the mountain. Harry is looking directly toward the bulge that was developing on the flank of the volcano. When the volcano erupted, the observation post was destroyed and the geologist Dave Johnston (not Harry), who replaced him that day of the eruption to allow Harry to return to UCSB where he was a PhD student and report to us about the volcano. Dave announced the eruption by radio to the World before the blast reached him and claimed his life. I knew Harry well (I was on his PhD committee), and the death of Dave hit him very hard. *(Courtesy of the Glicken Family)*

8

Volcanic Activity

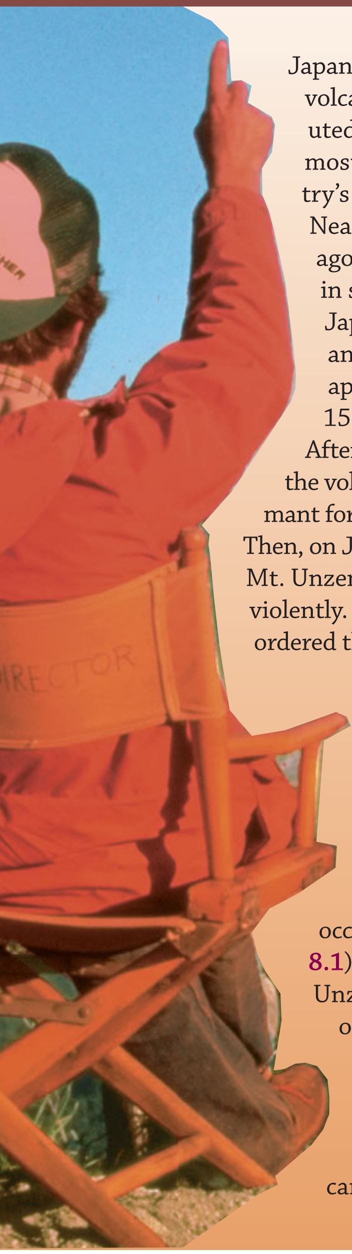
Learning Objectives

There are about 1,500 active volcanoes on Earth, almost 400 of which have erupted in the twentieth century. Volcanoes occur on all seven continents, as well as in the middle of the ocean. When human beings live in the path of an active volcano, the results can be devastating. In this chapter, we focus on the following learning objectives:

- **Know the major types of volcanoes, the rocks they produce, and their plate tectonic setting**
- **Understand the main types and effects of volcanic activity, including lava flows, pyroclastic activity, debris flows, and mudflows**
- **Understand the methods of studying volcanic activity, including seismic activity, topographic change, emission of gases, and geologic history, in order to better predict volcanic eruptions and minimize the hazards**

Case History

Mt. Unzen, 1991



Japan has 19 active volcanoes distributed throughout most of the country's landmass. Nearly 200 years ago, Mt. Unzen in southwestern Japan erupted and killed approximately 15,000 people. After this eruption, the volcano lay dormant for 200 years. Then, on June 3, 1991, Mt. Unzen erupted violently. Authorities ordered the evacuation of thousands of people. By the end of 1993, lava had erupted, and several thousand flows of hot ash had occurred (**Figure 8.1**). In fact, Mt. Unzen has the dubious honor of being one of the ash flow centers of the world. This volcano has provided

FIGURE 8.1 Ash flow Eruption of Mt. Unzen, Japan, June 1991. The cloud in the mountain area is moving rapidly downslope as an ash flow, and the firefighter is running for his life. *(AP Photo)*

8.1 Introduction to Volcanic Hazards

Worldwide, 50 to 60 volcanoes erupt each year. The United States experiences eruptions two or three times a year, with most of them occurring in Alaska.[1] Eruptions often occur in sparsely populated areas of the world, causing little or no loss of life or economic damage. However, when a volcano erupts near a densely populated area, the effects can be catastrophic.[3] Several hundred million people on Earth live close to volcanoes, and, as the human population grows, more and more people are living on the flanks, or sides, of active or potentially active volcanoes. In the past century, almost 100,000 people have been killed by volcanic eruptions; nearly 23,000 lives were lost in the last two decades of the twentieth century alone.[1,3] Densely populated

scientists with a natural laboratory for studying such flows.[1,2] The 1991 eruption also produced damaging mudflows. A specially designed channel was constructed to contain the mudflows, but, as seen in **Figure 8.2**, the flows overran the channel, burying many homes in mud.

Harry Glicken was one of the 44 people killed when Mt. Unzen erupted. Harry was a brave and dedicated young scientist who, through good fortune, had escaped death in the May 18, 1980, eruption of Mount St. Helens. Harry's death reminds us that being a volcanologist is a hazardous career path. They often risk their lives to better understand volcanoes and save the lives of people living nearby. *This chapter on volcanic processes is dedicated to Harry, who loved volcanoes and who was my friend.*

(a)

(b)

FIGURE 8.2 Mudflow (a) Mudflows from Mt. Unzen in 1991 damaged many homes in Shimabara, Japan. Flows overflowed the channels constructed to contain them. *(Michael S. Yamashita/Corbis)* (b) The flows inundated many homes and buildings. *(Michael S. Yamashita/Corbis)*

countries with many active volcanoes, such as Japan, Mexico (especially near Mexico City), the Philippines, and Indonesia, are particularly vulnerable.[2] The western United States, including Alaska, Hawaii, and the Pacific Northwest, also has many active or potentially active volcanoes; several of these volcanoes are located near large cities (**Figure 8.3**). **Table 8.1** (page 253) lists some historic volcanic events and their effects.

8.2 Volcanism and Volcanoes

Volcanic activity, or volcanism, is directly related to plate tectonics, and most active volcanoes are located near plate boundaries.[4] As spreading or sinking lithospheric plates interact with other Earth materials, **magma**, or molten rock, including a small component of dissolved gases, mostly water vapor and carbon dioxide, is produced (see A Closer

FIGURE 8.3 Locations of volcanoes in the United States Index maps show locations of active and potentially active volcanoes and nearby population centers (not all labeled). *(From Wright, T. L., and Pierson, T. C. 1992. U.S. Geological Survey Circular 1073)*

TABLE 8.1 Selected Historic Volcanic Events

Volcano or City	Year	Effect
Vesuvius, Italy	A.D. 79	Destroyed Pompeii and killed 16,000 people. City was buried by volcanic activity and rediscovered in 1595.
Skaptar Jokull, Iceland	1783	Killed 10,000 people (many died from famine) and most of the island's livestock. Also killed some crops as far away as Scotland.
Tambora, Indonesia	1815	Caused global cooling; killed 10,000 people and 80,000 starved; produced "year without a summer."
Krakatau, Indonesia	1883	Tremendous explosion; more than 36,000 deaths from tsunami.
Mount Pelée, Martinique	1902	Ash flow killed 30,000 people in a matter of minutes.
La Soufrière, St. Vincent	1902	Killed 2,000 people and caused the extinction of the Carib Indians.
Mount Lamington, Papua New Guinea	1951	Killed 6,000 people.
Villarica, Chile	1963–1964	Forced 30,000 people to evacuate their homes.
Mount Helgafell, Heimaey Island, Iceland	1973	Forced 5,200 people to evacuate their homes.
Mount St. Helens, Washington, United States	1980	Debris avalanche, lateral blast, and mudflows killed 57 people and destroyed more than 100 homes.
Nevado del Ruiz, Colombia	1985	Eruption generated mudflows that killed at least 22,000 people.
Mount Unzen, Japan	1991	Ash flows and other activity killed 41 people and burned more than 125 homes. More than 10,000 people evacuated.
Mount Pinatubo, Philippines	1991	Tremendous explosions, ash flows, and mudflows combined with a typhoon killed more than 740 people; several thousand people evacuated.
Montserrat, Caribbean	1995	Involved explosive eruptions, pyroclastic flows; south side of island evacuated, including capital city of Plymouth; several hundred homes destroyed.
Mount Nyiragongo, Congo, Africa	2002	Involved lava flows through 14 villages and part of the city of Gomo; several hundred thousand people evacuated, about 5,000 homes destroyed, and about 45 people killed.
Chaitén, Chile	2008	Involved explosive eruptions, pyroclastic flows; 5,000 people evacuated; disrupted aviation in South America for weeks.
Eyjafjallajokull, Iceland	2010	Large ash emission disrupted air travel in the United Kingdom and northern Europe for several weeks. Over 95,000 flights were canceled and losses to airlines exceeded $1 billion.
Mount Merapi, Indonesia	2010	Involved explosions and pyroclastic flows; 200,000 people evacuated and over 150 deaths.

Data partially derived from Ollier, C. 1969. *Volcanoes. Cambridge, MA: MIT Press.*

Look: How Magma Forms). Magma that has emerged from a volcano onto Earth's surface is called **lava**. Approximately two-thirds of all active volcanoes on Earth are located in the "ring of fire" that circumscribes the Pacific Ocean, an area corresponding to subduction zones on the border of the Pacific plate (**Figure 8.4**, page 256).

8.3 Volcano Types

Each type of volcano has a characteristic style of activity that is partly a result of the viscosity of the magma. *Viscosity* describes a liquid's resistance to flow, with a high viscosity indicating a high resistance to flow. For example, honey is more viscous

A Closer Look

How Magma Forms

With the exception of the outer core deep within Earth's interior, the planet is almost completely composed of solid rock (see Sections 2.1 and 2.2). So where does the magma that forms volcanoes at the surface come from?

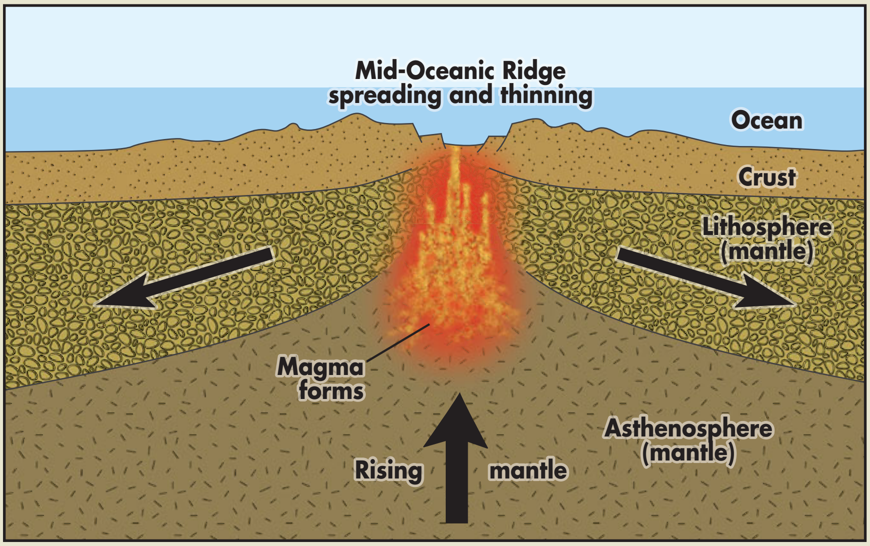
Most magmas come from the asthenosphere, the weak layer that underlies the lithospheric plates (see Section 2.1). The asthenosphere is weak and able to flow, allowing rigid plates of lithosphere to move around the globe; although the asthenosphere is not actually molten, it is close to the temperature at which it would melt. As a result, the asthenosphere is more prone to melting than are the overlying lithosphere and the lower mantle.[5] Two important ways in which silicate rocks of the asthenosphere melt include decompression and the addition of volatiles (especially water). These processes are closely tied to plate tectonic processes:

1. **Decompression melting** occurs when the overlying pressure exerted on hot rock within the asthenosphere is decreased. The melting temperature for mantle silicate rocks at Earth's surface is approximately 1,200° C (2,200° F).[4] Within the mantle, this temperature is exceeded within the upper 100 km (62 mi) of Earth.[5] As with temperature, pressure increases with depth, and the great pressure generated by the weight of overlying rock keeps Earth's mantle in a solid state far above the surface melting temperature of the rock. However, if the pressure is released without a change in temperature, the rocks will melt. Decompression melting happens at divergent plate boundaries, continental rifts, and hot spots. At divergent plate boundaries and continental rifts, the lithosphere is stretched and thinned. This thinning causes the mantle to upwell toward the surface and lowers the pressure (because there is less overlying rock). With lower pressure and high temperature, decompression melting occurs (**Figure 8.Aa**).
2. **Addition of volatiles** lowers the melting temperature of rocks by helping to break chemical bonds within silicate minerals. Consequently, rocks that are close to their melting temperature will melt in the presence of added volatiles. **Volatiles** are chemical compounds, such as water (H_2O) and carbon dioxide (CO_2), that evaporate easily and exist in a gaseous state at Earth's surface. Such volatiles are often incorporated into minerals formed on the seafloor or within the oceanic lithosphere and are released when oceanic plates are subducted. The released volatiles rise upward from the subducting slab and interact with the formerly dry asthenosphere and induce melting and volcanism at Earth's surface (Figure 8.Ab).[5] Subduction zone volcanism results in most of the on-land volcanoes around the world and is exemplified by the "ring of fire" that surrounds the Pacific plate (see Figure 8.4).

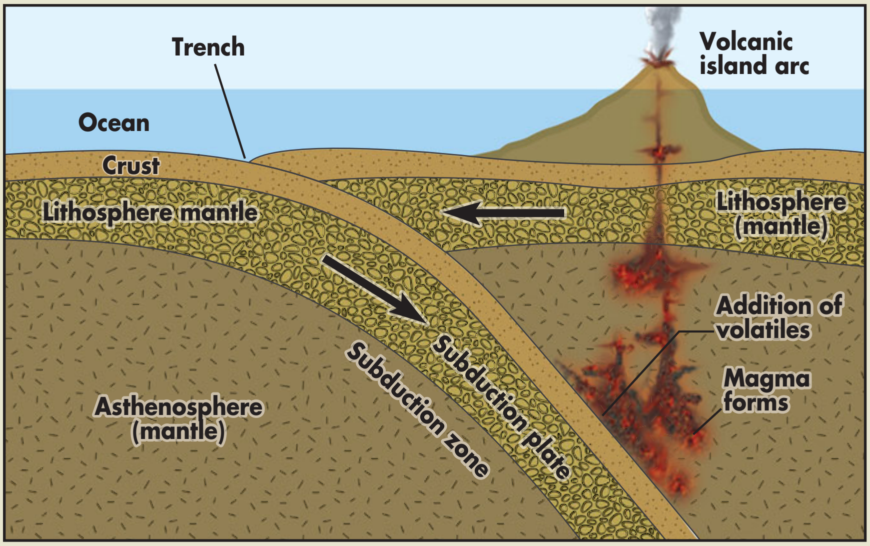
than water. Magma viscosity is determined by both its silica (SiO_2) content, which can vary from about 50 to 70 percent, and its temperature. The higher the silica content of a magma, the more viscous it is. Also, the hotter the magma is, the less viscous it is. The effect of temperature may make sense to you if you think about honey again. If you keep honey in the refrigerator, it becomes very difficult to pour or squeeze out of its container. However, if it is stored in a cabinet or heated slightly before serving, it flows much more readily. Highly viscous magmas often erupt explosively, whereas less viscous magmas tend to flow. **Table 8.2** (page 256) lists the types of volcanoes and their characteristics.

Shield Volcanoes

Shield volcanoes are by far the largest volcanoes. They are common in the Hawaiian Islands and are also found in Iceland and some islands in the Indian Ocean (**Figure 8.5**, page 257). Shield volcanoes are shaped like a gentle arch, or shield. They are among the tallest mountains on Earth when measured from their base, often located on the ocean floor. Shield



(a)



(b)

FIGURE 8.A Two ways magma may form Magma is generated primarily within the asthenosphere. (a) Decompression melting occurs when the overburden pressure on asthenospheric rocks is decreased by thinning of the overlying lithospheric plate, causing upwelling of superheated rocks. (b) Melting at subduction zone due to addition of volatiles (especially water) to the asthenosphere released from minerals contained in the sediment and rock of the downgoing oceanic plate.

volcanoes are characterized by generally nonexplosive eruptions, which result from the relatively low silica content (about 50 percent) of the magma. When a shield volcano erupts, lava tends to flow down the sides of the volcano rather than explode violently into the atmosphere. The common rock type formed by the magma of shield volcanoes is *basalt*, composed mostly of feldspar and ferromagnesian minerals. (See Chapter 3 for a review of mineral and rock types.)

Shield volcanoes are built up almost entirely from numerous lava flows, but they can also produce a lot of tephra. *Tephra*, also referred to as *pyroclastic debris*, includes all types of volcanic debris that are explosively ejected from a volcano. Debris particles range from *ash*, less than 2 mm (0.08 in.) in diameter, to *cinders*, 4 to 32 mm (0.16 to 1.26 in.) in diameter, to *blocks* and *bombs* greater than 64 mm (2.52 in.) in diameter. Accumulation of tephra forms *pyroclastic deposits* (Greek *pyro*, "fire," and *klastos*, "broken"). Pyroclastic deposits may be consolidated to form *pyroclastic rocks*.

The slope of a shield volcano is very gentle near the top, but it increases on the flanks. This change is due to the viscosity of the flowing lava. When

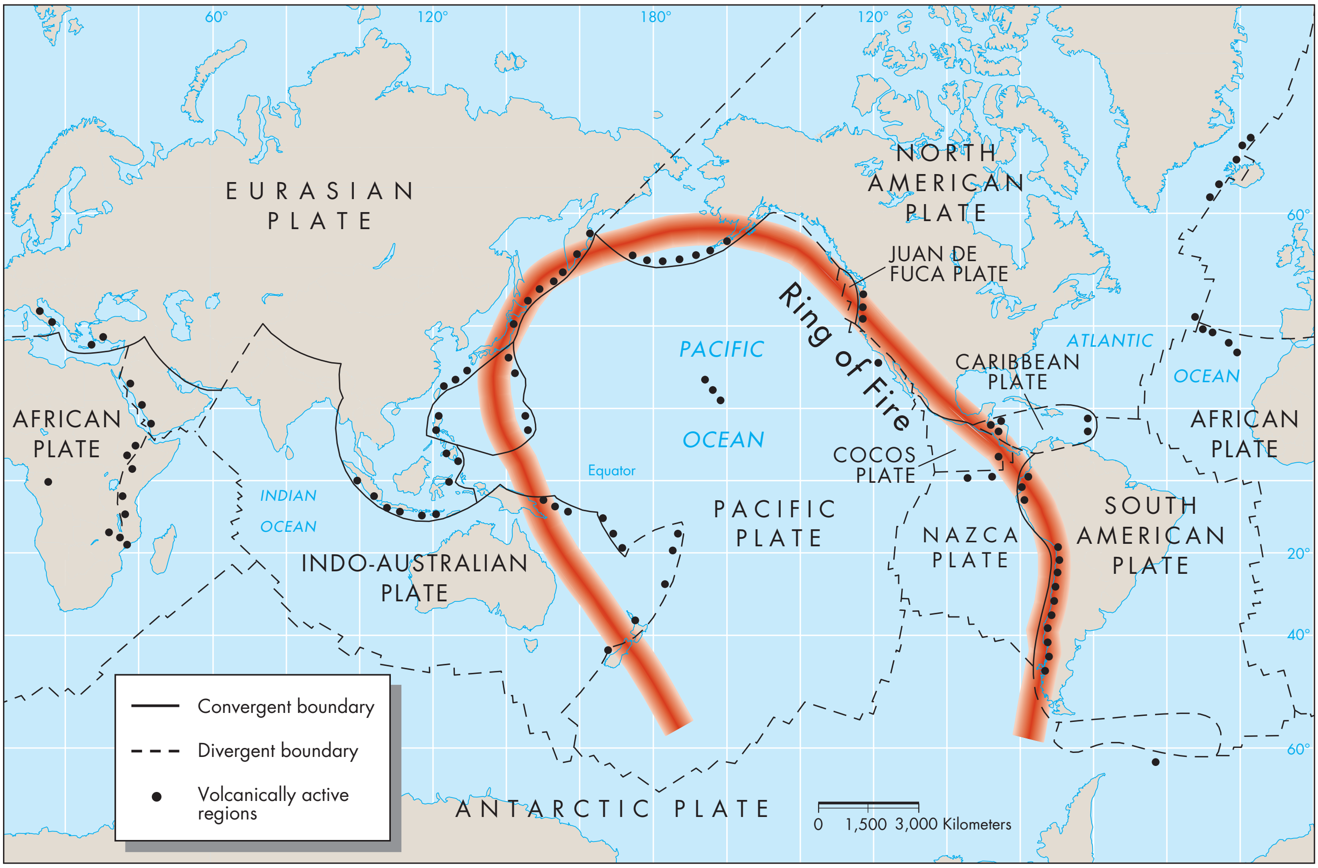


FIGURE 8.4 The "ring of fire" The ring of fire surrounds the Pacific plate. *(Modified from Costa, J. E., and Baker, V. R. 1981.* Surficial Geology. *Originally published by John Wiley and Sons, New York, and republished by Tech Books, Fairfax, VA)*

TABLE 8.2 Types of Volcanoes

Volcano Type	Shape	Silica Content of Magma	Viscosity	Rock Type Formed	Eruption Type	Example
Shield volcano	Gentle arch, or shield shape, with shallow slopes; built up of many lava flows	Low	Low	Basalt	Lava flows, tephra ejections	Mauna Loa, Hawaii Figure 8.5
Composite volcano, or stratovolcano	Cone-shaped; steep sides; built up of alternating layers of lava flows and pyroclastic deposits	Intermediate	Intermediate	Andesite	Combination of lava flows and explosive activity	Mt. Fuji, Japan Figure 8.7
Volcanic dome	Dome shaped	High	High	Rhyolite	Highly explosive	Mt. Lassen, CA Figure 8.8
Cinder cone	Cone shaped; steep sides; often with summit crater	Low	Low	Basalt	Tephra (mostly ash) ejection	Springerville, AZ Figure 8.9

FIGURE 8.5 Shield volcano Profile of a shield volcano. Notice that the profile to the summit is very gently curved, like a warrior's shield. The mountain shown is Mauna Loa, Hawaii, as viewed from the Hawaiian Volcanic Observatory. *(University of Washington Libraries)*

FIGURE 8.6 Lava tube 1984 Mauna Loa, Hawaii, eruption. *(Scott Lopez/Wind Cave National Park)*

magma comes out of *vents*, or openings, at the top of the volcano, it is quite hot and flows easily. As it flows down the sides of the volcano, it cools and becomes more viscous, so a steeper slope is needed for it to travel farther downslope.

In addition to flowing down the sides of a volcano, lava can move away from a vent in a number of ways. Magma often moves for many kilometers underground in *lava tubes*. These tubes are often very close to the surface, and they insulate the magma, keeping it hot and fluid. After the lava cools and crystallizes to rock, the lava tubes may be left behind as long, sinuous cavern systems (**Figure 8.6**). They form natural conduits for movement of groundwater and may cause engineering problems when they are encountered during construction projects.

A shield volcano may have a *summit caldera*, which is a steep, walled basin often 10 km (6.2 mi) or more in diameter. A summit caldera is formed by collapse of the summit of the volcano, in which a lava lake may form and from which lava may flow during an eruption. Eruptions of lava from shield volcanoes also commonly occur along linear fractures known as rift zones on the flank of a volcano. For example, rift eruptions at the Hawaiian shield volcano Kilauea, on the big island of Hawaii, during the past several decades continue to add new land to the island.[4]

FIGURE 8.7 Composite volcano Mt. Fuji, Japan, is a composite volcano with beautiful steep sides. *(Jon Arnold Images/Alamy)*

FIGURE 8.8 Eruption of Mt. Lassen June 1914. *(Courtesy of B. F. Loomis/Lassen Volcanic National Park)*

Composite Volcanoes

Composite volcanoes are known for their beautiful cone shape (Figure 8.7). Examples in the United States include Mount St. Helens and Mt. Rainier, both in Washington State. Composite volcanoes are characterized by magma with an intermediate silica content (about 60 percent), which is more viscous than the lower-silica magma of shield volcanoes. The common rock type formed by the magma of composite volcanoes is *andesite*, composed mostly of soda and lime-rich feldspar and ferromagnesian minerals, with small amounts of quartz. Composite volcanoes are distinguished by a mixture of explosive activity and lava flows. As a result, these volcanoes, also called *stratovolcanoes*, are composed of alternating layers of pyroclastic deposits and lava flows. Their steep flanks are due to the angle of repose, or the maximum slope angle for loose material, which for many pyroclastic deposits is approximately 30 percent to 35 percent.

Don't let the beauty of these mountains fool you. Because of their explosive activity and relatively common occurrence, composite volcanoes are responsible for most of the volcanic hazards that have caused death and destruction throughout history. As the 1980 eruption of Mount St. Helens demonstrated, they can produce gigantic horizontal blasts, similar in form to the blast of a shotgun. We should consider such volcanoes armed and dangerous.

Volcanic Domes

Volcanic domes are characterized by viscous magma with a relatively high silica content (about 70 percent). The common rock type produced by this magma is *rhyolite*, composed mostly of potassium- and sodium-rich feldspar, quartz, and minor amounts of ferromagnesian minerals. The activity of volcanic domes is mostly explosive, making these volcanoes very dangerous. Mt. Lassen in northeastern California is a good example of a volcanic dome. Mt. Lassen's last series of eruptions, from 1914 to 1917, included a tremendous lateral blast that affected a large area (Figure 8.8).

Cinder Cones

Cinder cones are relatively small volcanoes formed from tephra, mostly volcanic ash and larger particles, including volcanic bombs. Bombs are formed from blobs of ejected lava that spin in the air and take on a rounded shape with tapered ends. Cinder cones grow from the accumulation of tephra near a volcanic vent. They are often found on the flanks of larger volcanoes or along normal faults and long cracks or fissures (**Figure 8.9**).

The Paricutín cinder cone (**Figure 8.10**) in the Itzicuaro Valley of central Mexico, west of Mexico City, offered a rare opportunity to observe the birth and rapid growth of a volcano at a location where none had existed before. On February 20, 1943, after several weeks of earthquakes and sounds like

FIGURE 8.9 Cinder cone Cinder cone with a small crater at the top near Springerville, Arizona. The brownish-black material from the center-upper part of the photograph to the upper-right corner is a lava flow that originates from the base of the cinder cone. *(Michael Collier)*

FIGURE 8.10 Rapid growth of a volcano Paricutín cinder cone, central Mexico, 1943, erupting ash and lava. A lava flow has nearly buried the village of San Juan Parangaricutiro, leaving the church steeple exposed. *(Courtesy of Tad Nichols)*

thunder coming from beneath the surface of Earth, an astounding event occurred. As Dionisio Pulido was preparing his cornfield for planting, he noticed that a hole in the ground he had been trying to fill for years had opened wider. As Señor Pulido watched, the surrounding ground swelled, rising over 2 m (6.5 ft), and sulfurous smoke and ash began billowing from the hole. By that night, the hole was ejecting glowing red rock fragments high into the air. By the next day, the cinder cone had grown as high as a three-story building, as rocks and ash continued to be blown into the sky by the eruption. After only 5 days, the cinder cone had grown to the height of a 30-story building. In June 1944, a fissure that had opened in the base of the now 400 m (1,312 ft)-high cone erupted a thick lava flow that overran the nearby village of San Juan Parangaricutiro, leaving little but the church steeple exposed (see Figure 8.10). No one was killed by the ash or lava flow, and, within a decade, Paricutín cinder cone became a dormant volcano. Nevertheless, the years of eruption from Dionisio's cornfield had significant local impacts. Crops failed; they were sometimes buried by ash faster than they could grow; and livestock became sick and died. Some people relocated to other areas, and others moved back to the area. Locating property boundaries was difficult because boundary markers were often covered by ash and lava, resulting in property disputes.[6]

8.4 Volcano Origins

We established earlier that the causes of volcanic activity are directly related to plate tectonics.[4] Understanding the tectonic origins of different types of volcanoes helps explain the chemical differences in their rock types. **Figure 8.11** is an idealized diagram showing the relationship of processes at plate boundaries to the volcano types we have described. The following features are illustrated in the diagram:

1. Volcanism occurring at mid-oceanic ridges produces basaltic rock (decompression melting). Basaltic rock has a relatively low silica content and wells up directly from the asthenosphere as magma. The basaltic magma mixes very little with other materials except oceanic crust, which itself is basaltic. Where these spreading ridge systems occur on land, as, for example, in Iceland, shield volcanoes are formed (**Figure 8.12**).
2. Shield volcanoes are formed above hot spots located below the lithospheric plates. For example, the Hawaiian volcanoes are located well within the Pacific plate rather than near a plate

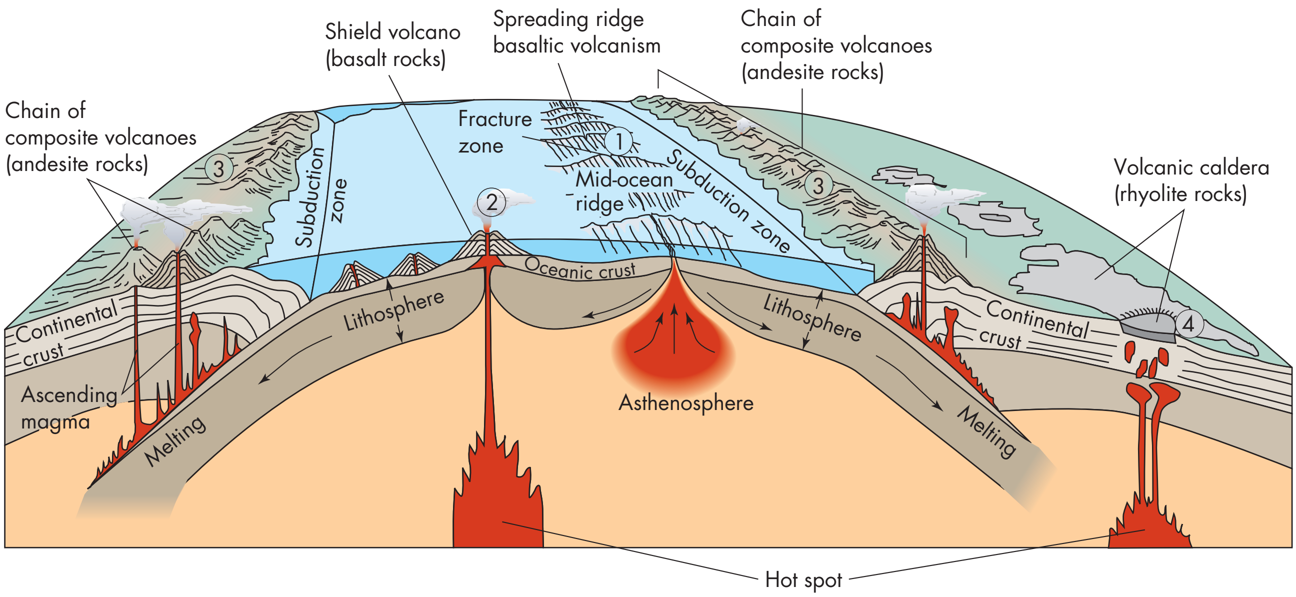


FIGURE 8.11 Volcanic activity and plate tectonics Idealized diagram showing plate tectonic processes and their relation to volcanic activity. Decompression melting occurs at the mid-oceanic ridge and melting by addition of volatiles occurs at the subduction zones (see Figure 8.A) . Numbers refer to explanations in the text. *(Modified from Skinner, B. J., and Porter, S. C. 1992.* The Dynamic Earth, *2nd ed. New York: John Wiley)*

FIGURE 8.12 Fissure on the Mid-Atlantic Ridge Icelandic shield volcano (background) and large fissure (normal fault) associated with spreading of tectonic plates along the Mid-Atlantic Ridge. *(University of Washington Libraries)*

boundary. It is currently believed that there is a hot spot below the Pacific plate where magma is generated. Magma moves upward through the plate and produces a volcano on the bottom of the sea; such a volcano may eventually become an island. The plate containing the Hawaiian Islands is moving roughly northwest over the stationary hot spot; therefore, a chain of volcanoes running northwest to southeast is formed (see Chapter 2). The island of Hawaii is presently near the hot spot and is experiencing active volcanism and growth. Islands to the northwest, such as Molokai and Oahu, have evidently moved off the hot spot, since the volcanoes on these islands are no longer active.

3. Composite volcanoes are associated with andesitic volcanic rocks and subduction zones (melting due to addition of volatiles). These are the most common volcanoes found around the Pacific Rim. For example, volcanoes in the Cascade Range of Washington, Oregon, and California are related to the Cascadia subduction zone (Figure 8.13). Andesitic volcanic rocks are produced at subduction zones, where rising magma mixes with both oceanic and continental crust. Since continental crust has a higher silica content than basaltic magma, this process produces rock with an intermediate silica content.
4. Caldera-forming eruptions may be extremely explosive and violent. These eruptions tend to be associated with rhyolitic rocks, which are produced when magma moves upward and mixes with continental crust. Rhyolitic rocks contain more silica than other volcanic rocks because of the high silica content of continental crust. Volcanic domes, although not always associated with caldera-forming eruptions, are usually found inland of subduction zones and erupt silica-rich rhyolitic magma as well.

Our brief discussion does not explain all differences in composition and occurrence of basaltic, andesitic, and rhyolitic rocks. However, it does establish the most basic relationships between plate tectonics, volcanic activity, and volcanic rocks.

8.5 Volcanic Features

Geologic features that are often associated with volcanoes or volcanic areas include craters, calderas, volcanic vents, geysers, and hot springs.

Craters, Calderas, and Vents

Depressions commonly found at the top of volcanoes are *craters*. Craters form by explosion or collapse of the upper portion of the volcanic cone and may be flat floored or funnel shaped. They are usually a few kilometers in diameter. *Calderas* are gigantic, often circular, depressions resulting from explosive ejection of magma and subsequent collapse of the upper portion of the volcanic cone. They may be 20

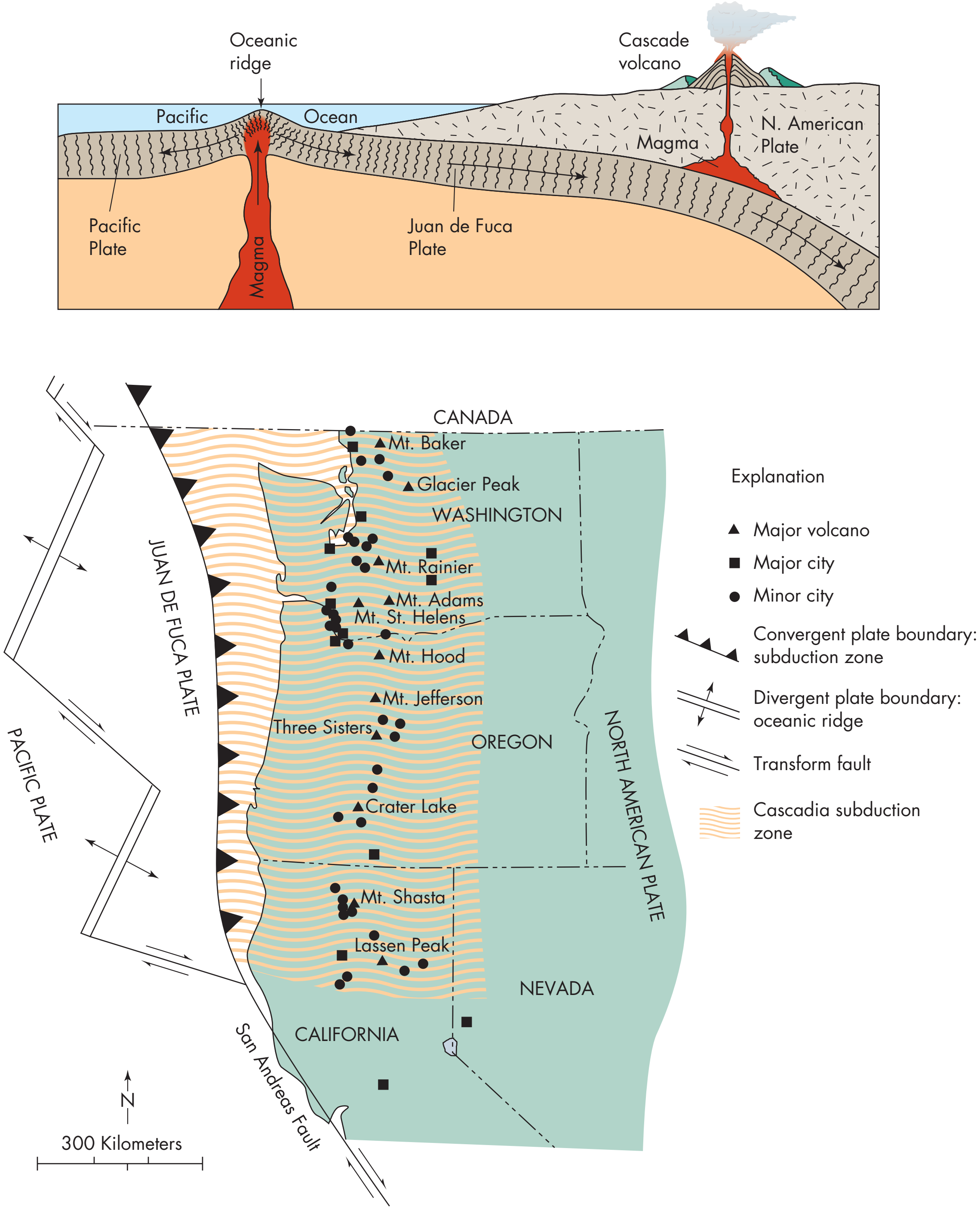


FIGURE 8.13 Cascade volcanoes and plate tectonics Map and plate tectonic setting of the Cascade Range, showing major volcanoes and cities in their vicinity. *(Modified after Crandell, D. R., and Waldron, H. H. 1969.* Disaster Preparedness. *Office of Emergency Preparedness)*

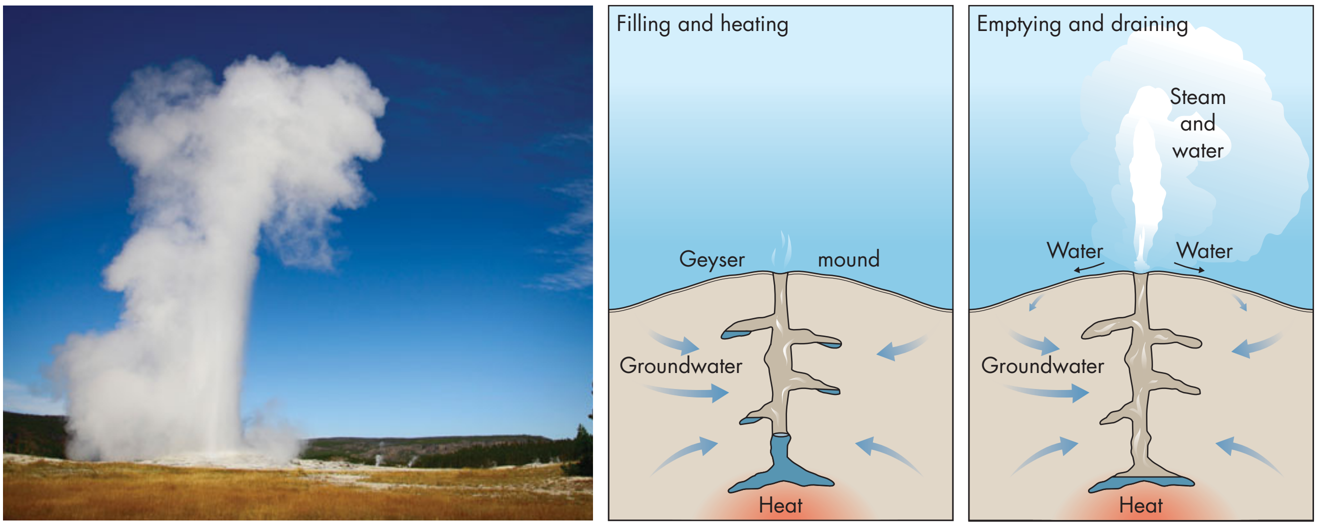
or more kilometers in diameter and contain volcanic vents as well as other volcanic features, such as gas vents and hot springs. *Volcanic vents* are openings through which lava and pyroclastic debris are erupted at the surface of Earth. Vents may be roughly circular conduits, and eruptions construct domes and cones. Other vents may be elongated fissures or rock fractures, often normal faults, which produce lava flows. Some extensive fissure eruptions have produced huge accumulations of nearly

horizontal basaltic lava flows called *flood basalts*. The best-known flood basalt deposit in the United States is the Columbia Plateau region (**Figure 8.14**) in parts of Washington, Oregon, and Idaho, where basalt covers a vast area.

Hot Springs and Geysers

Hot springs and geysers are hydrologic features found in some volcanic areas. Groundwater that comes into contact with hot rock becomes heated, and, in some cases, the heated water discharges at the surface as a *hot spring*, or *thermal spring*. In rare cases, the subsurface groundwater system involves circulation and heating patterns that produce periodic release of steam and hot water at the surface, a phenomenon called a *geyser*. World-famous geyser basins or fields are found in Iceland, New Zealand, and Yellowstone National Park in Wyoming (**Figure 8.15**).

FIGURE 8.14 Flood basalt Columbia Plateau flood basalts along the bluff of the Columbia River in Benton County, Washington. *(Calvin Larsen/Photo Researchers, Inc.)*



(a)

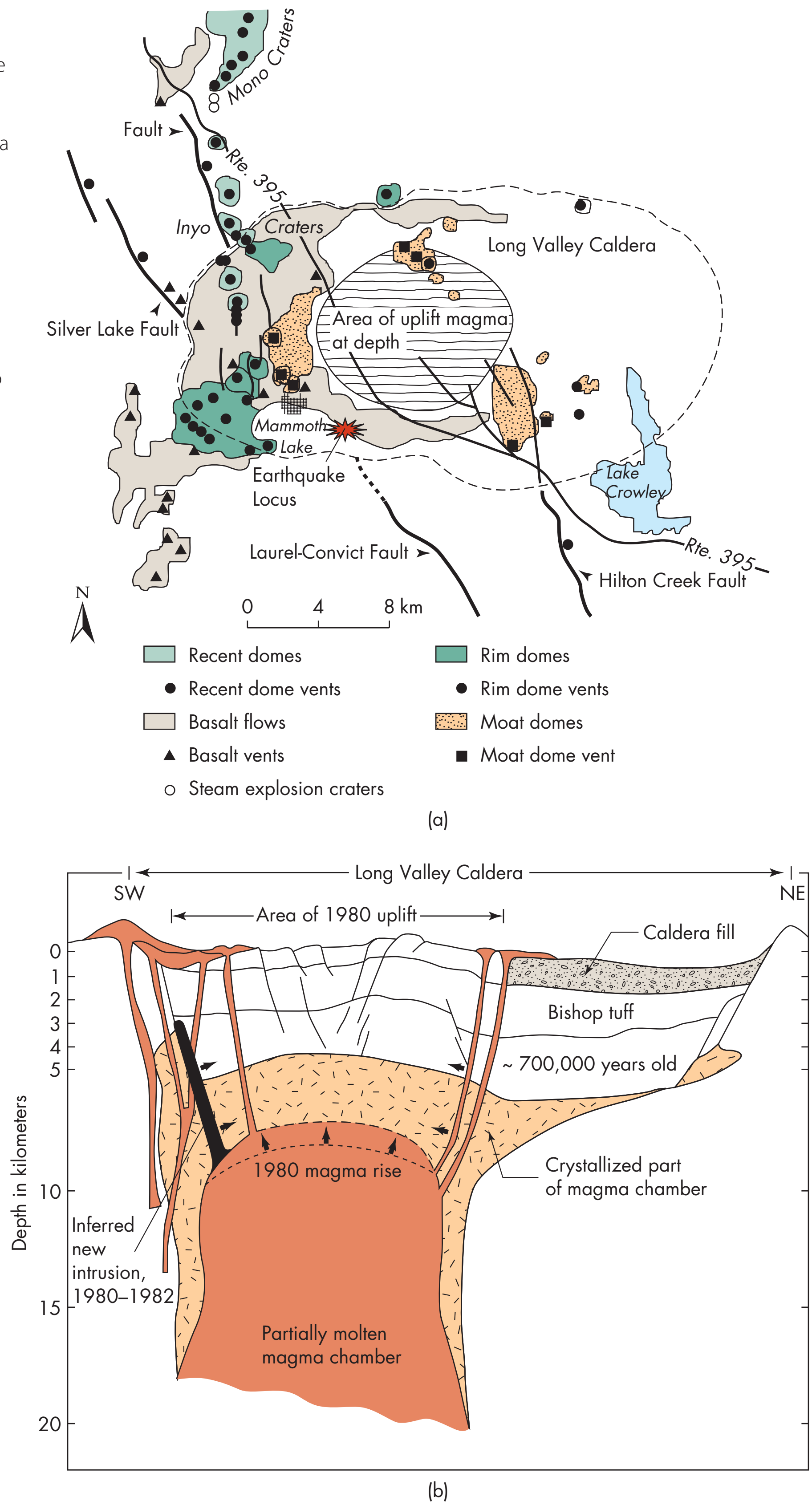
(b)

FIGURE 8.15 How a geyser works (a) Eruption of Old Faithful Geyser, Yellowstone National Park, Wyoming. The geyser is named for its very predictable periodic eruption. *(zbindere/iStockphoto)* (b) Schematic drawing of a geyser, illustrating processes that lead to eruption.

Groundwater fills subsurface geyser's irregular tubes and water is heated until it flashes to steam and erupts.

Eruption partly empties subsurface tubes and recycled groundwater starts the filling process again. Water running off precipitates a white silica-rich mineral called geyserite that forms the geyser mound.

FIGURE 8.16 Caldera geology Map (a) and diagram (b) illustrating the volcanic hazard near Mammoth Lakes, California. The map (a) shows the location of past volcanic events, the area of uplift where magma seems to be moving up, and, finally, the area where earthquake swarms have occurred near Mammoth Lakes. The geological cross section (b) shows a section (north-east–southwest) through the Long Valley caldera. Shown are geologic relations inferred for the 1980 magma rise that produced uplift and swarms of earthquakes. *(From Bailey, R. A. 1983. Mammoth Lakes earthquakes and ground uplift: Precursor to possible volcanic activity? In U.S. Geological Survey Yearbook, Fiscal Year 1982)*



Caldera Eruptions

Calderas are produced by very rare but extremely violent eruptions. Although none have occurred anywhere on Earth in the past few hundred thousand years, at least 10 **caldera eruptions** have occurred in the past million years, 3 of them in North America. A large caldera-forming eruption may explosively extrude up to 1,000 km^3 (240 mi^3) of pyroclastic debris, consisting mostly of ash. This is approximately 1,000 times the quantity ejected by the 1980 eruption of Mount St. Helens! Such an eruption could produce a caldera more than 10 km (6.2 mi) in diameter and blanket an area several tens of thousands of square kilometers with ash. These ash deposits can be 100 m (328 ft) thick near the crater's rim and a meter or so thick 100 km (62 mi) away from the source.[7] The most recent caldera-forming eruptions in North America occurred about 600,000 years ago at Yellowstone National Park in Wyoming and 700,000 years ago in Long Valley, California. Volcanic features and the geology of the Long Valley caldera are shown in **Figure 8.16**. **Figure 8.17a** shows the area covered by ash in the eruption event, which produced the Long Valley caldera near the famous Mammoth Mountain ski resort. Figure 8.17b shows the potential hazard from a future volcanic eruption at Long Valley. The most recent volcanic eruptions at Long Valley were about 400 years ago. Measurable uplift of the land accompanied by swarms of earthquakes up to M 6 in the early 1980s suggested that magma was moving upward, prompting the U.S. Geological Survey to issue a potential volcanic hazard warning that was subsequently lifted. However, the future of Long Valley remains uncertain.

The main events in a caldera-producing eruption can occur quickly—in a few days to a few weeks—

(a)

(b)

FIGURE 8.17 Potential hazards Potential hazards from a volcanic eruption at the Long Valley caldera near Mammoth Lakes, California. (a) Area covered by ash from the Long Valley caldera eruption approximately 700,000 years ago. The circle near Long Valley (LV) has a radius of 120 km (75 mi) and encloses the area that would be subject to at least 1 m (3.3 ft) of downwind ash accumulation if a similar eruption were to occur again. Also within this circle, hot pyroclastic flows (ash flows) are likely to occur and, in fact, could extend farther than shown by the circle. (b) The red area and diagonal lines show the hazard from flowage events out to a distance of approximately 20 km (12.5 mi) from recognized potential vents. Lines surrounding the hazard areas represent potential ash thicknesses of 20 cm (8 in.) at 35 km (22 mi) (dashed line), 5 cm (2 in.) at 85 km (53 mi) (dotted line), and 1 cm (0.4 in.) at 300 km (186 mi) (solid line). These estimates of potential hazards assume an explosive eruption of approximately 1 km^3 (0.24 mi^3) from the vicinity of recently active vents. *(From Miller, C. D., Mullineaux, D. R., Crandell, D. R., and Bailey, R. A. 1982.* Potential hazards from future volcanic eruptions in the Long Valley–Mono Lake area, east-central California and southwest Nevada—A preliminary assessment. *U.S. Geological Survey Circular 877)*

but intermittent, lesser-magnitude volcanic activity can linger for a million years. Thus, the Yellowstone event has left us hot springs and geysers, including Old Faithful, while the Long Valley event has left us a potential volcanic hazard. In fact, both sites are still capable of producing volcanic activity because magma is still present at variable depths beneath the caldera floors. Both are considered *resurgent* calderas because their floors have slowly domed upward since the explosive eruptions that formed them. The most likely future eruptions for Long Valley or Yellowstone would be much smaller than the giant caldera eruptions that occurred hundreds of thousands of years ago.

8.6 Volcanic Hazards

Volcanic hazards include the *primary effects* of volcanic activity that are the direct results of the eruption and *secondary effects*, which may be caused by the primary effects. Primary effects are lava flows; pyroclastic activity, including ash fall, ash flows, and lateral blasts; and the release of gases. Most of the gases released are steam, but corrosive or poisonous gases may also be released. Secondary effects include debris flows, mudflows, landslides, or debris avalanches, floods, and fires. At the planetary level, large eruptions can cause global cooling of the atmosphere for a year or so.[7,8]

Lava Flows

Lava flows are one of the most familiar products of volcanic activity. They result when magma reaches the surface and overflows the crater or a volcanic vent along the flanks of the volcano. The three major groups of lava take their names from the volcanic rocks they form: basaltic (by far the most abundant of the three), andesitic, and rhyolitic.

Lava flows can be quite fluid and move rapidly, or they can be relatively viscous and move slowly. Basaltic lavas, composed of approximately 50 percent silica, exhibit a range of velocities. Basaltic lavas with lower viscosity and higher eruptive temperatures are the fastest moving, with a usual velocity of a meter or so per hour (around 3.2 ft per hour) but may be much faster on a steep slope. These lavas, called *pahoehoe* lavas (pronounced pa-hoy-hoy), have a smooth, *ropy* surface texture when they harden (**Figure 8.18a**). Cooler, more viscous basaltic lava flows move at rates of a few meters per day and have a *blocky* texture after hardening (**Figure 8.18b**). This type of basaltic lava is called *aa* (pronounced ah-ah). With the exception of some flows on steep slopes, most lava flows are slow enough that people can easily move out of the way as they approach.[9]

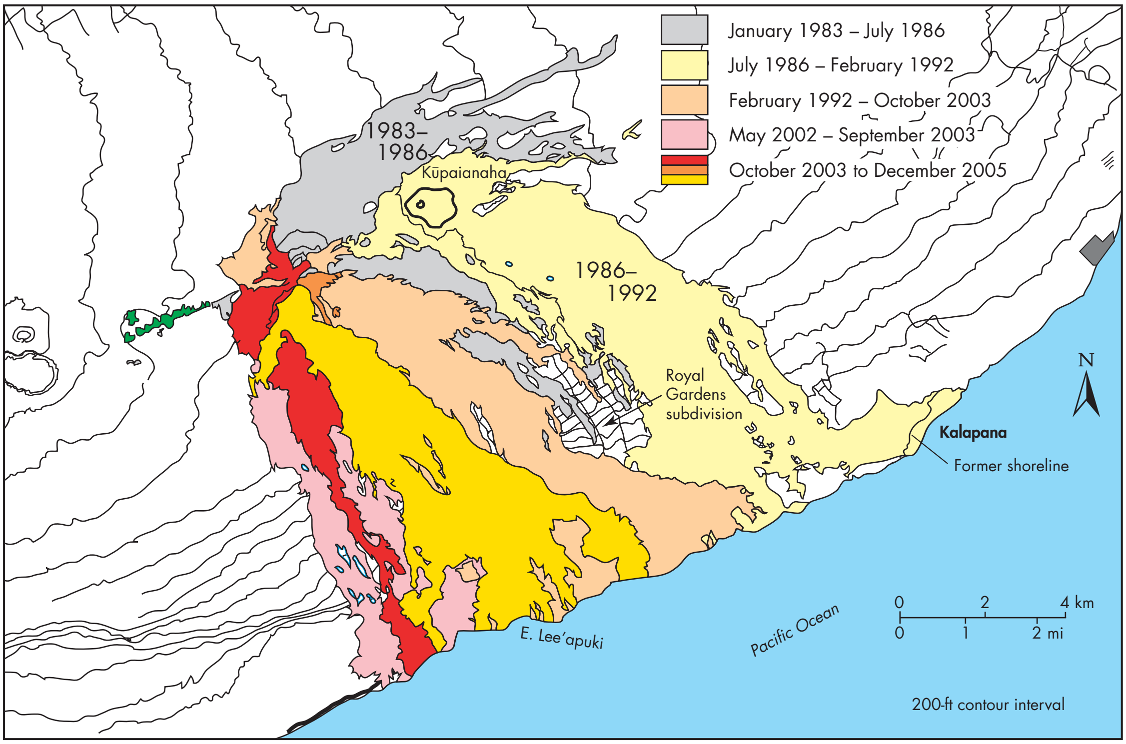
Lava flows from rift eruptions on Kilauea, Hawaii, began in 1983 and have become the longest and largest eruptions of Kilauea in history[4] (**Figure 8.19**). By 2005, more than 100 structures in the village of Kalapana had been destroyed by lava flows, including the National Park Visitor Center. Lava flowed across part of the famous Kaimu Black Sand Beach and into the ocean. The village of Kalapana has virtually disappeared, and it will be many decades before much of the land is productive again. The eruptions, in concert with beach processes, have produced new black sand beaches. The sand is produced when the molten lava enters the relatively cold ocean waters and shatters into sand-sized particles.

Methods to Control Lava Flows

Several methods, such as hydraulic chilling and wall construction, have been employed to deflect lava flows away from populated or otherwise valuable areas. These methods have had mixed success. They cannot

FIGURE 8.18a *Pahoehoe* lava flow With a smooth surface texture, surrounding and destroying a home at Kalapana, Hawaii, in 1990. Such flows destroyed more than 100 structures, including the National Park Service Visitor Center. These types of flows are often called *ropy lava* because of the surface texture, which looks a bit like pieces of rope lying side by side as if coiled. *(Paul Richards/UPI/Corbis)*

FIGURE 8.18b *Aa* lava flow Blocky *aa* lava flow engulfing a building during the eruption on the island of Heimaey, Iceland. *(Solarfilma EHF)*



(a)

(b)

FIGURE 8.19 Lava flows on the island of Hawaii, 1983–2005 (a) Map of flows. (b) Lava flowing into the ocean. The white "smoke" is steam. The eruption illustrates the process that continues to build Hawaii. *(Hawaiian Volcano Observatory/USGS)*

be expected to modify large flows, and their effectiveness with smaller flows requires further evaluation.

Hydraulic chilling of lava flows, or cooling the flow with water, has sometimes been successful in reducing damage from volcanic eruptions. The world's most ambitious hydraulic chilling program was initiated in January 1973 on the Icelandic island of Heimaey, when basaltic lava flows from Mt. Helgafell nearly closed the harbor of the island's main town, Vestmannaeyjar, threatening the continued use of the island as Iceland's main fishing port. The situation prompted immediate action.

Three favorable conditions existed: (1) Flows were slow moving, allowing the necessary time to initiate a control program; (2) transport by sea and local roads allowed for the transport of pipes, pumps, and heavy equipment; and (3) water was readily available. Initially, the edges and surface of the flow were cooled with water from numerous fire hoses fed from a pipe (**Figure 8.20**). Then bulldozers were moved up on the slowly advancing flow, making a track or road on which the plastic pipe was placed. The pipe did not melt as long as water was flowing in it, and small holes in the pipe also helped cool particularly hot spots along various parts of the flow. Watering near the front of the flow had little effect the first day, but then flow began to slow down and in some cases stopped.

The action taken in Iceland undoubtedly had an important effect on the lava flows from Mt. Helgafell. It tended to restrict lava movement and, thus, reduced

(a)

(b)

(c)

FIGURE 8.20 People fighting lava flows Eruptions of Mt. Helgafell on the island of Heimaey, Iceland. (a) At night from the harbor area. *(Solarfilma EHF)* (b) Aerial view toward the harbor. Notice the advancing lava flow with the white steam escaping in the lower-right corner. The steam is the result of water being applied to the front of the flow. A water cannon is operating in the lower-right corner, and the stream of water is visible. *(James R. Andrews)* (c) Aerial view showing the front of the blocky lava flow encroaching into the harbor. By fortuitous circumstances, the flows stopped at a point that actually has improved the harbor by providing better protection against storm waves. *(James R. Andrews)*

property damage in the harbor town so that after the outpouring of lava stopped in June 1973, the harbor was still usable.[10] In fact, by fortuitous circumstances, the shape of the harbor was actually improved, with the new rock providing additional protection from the sea.

Pyroclastic Activity

Pyroclastic activity describes explosive volcanism, in which tephra is physically blown from a volcanic vent into the atmosphere. Several types of pyroclastic activity can occur. In *volcanic ash eruptions*, or **ash fall**, a tremendous quantity of rock fragments, natural glass fragments, and gas is blown high into the air by explosions from the volcano. **Lateral blasts** are explosions of gas and ash from the side of a volcano that destroy part of the mountain. The ejected material travels away from the volcano at tremendous speeds. Lateral blasts can be very destructive, and sometimes the velocity of the ejected material is nearly the speed of sound. (See the discussion of Mount St. Helens in Section 8.7 of this chapter.) *Pyroclastic flows*, or **ash flows**, are some of the most lethal aspects of volcanic eruptions. They are avalanches of very hot pyroclastic materials—ash, rock, volcanic glass fragments, and gas—that are blown out of a vent and move very rapidly down the sides of the volcano. Pyroclastic flows are also known as hot avalanches, or *nueé ardentes*, which is French for "glowing cloud."

Ash Fall. Volcanic ash eruptions can cover hundreds or even thousands of square kilometers with a carpet of volcanic ash. Ash eruptions create several hazards:

- Vegetation, including crops and trees, may be destroyed.
- Surface water may be contaminated by sediment, resulting in a temporary increase in acidity of the water. The increase in acidity generally lasts only a few hours after the eruption ceases.
- Structural damage to buildings may occur, caused by the increased load on roofs (**Figure 8.21**). A depth of only 1 cm (0.4 in.) of ash places an extra 2.5 tons of weight on the roof of an average house.
- Health hazards, such as irritation of the respiratory system and eyes, are caused by contact with the ash and associated caustic fumes.[9]
- Engines of jetliners may "flame out" as melted silica-rich ash forms a thin coating of volcanic glass in the engines. For example, the 1989 eruption of Redoubt Volcano in Alaska produced an ash eruption cloud that an airliner on the way to Japan encountered. Power to all four engines of the jetliner was lost. Fortunately, the engines restarted within about 5 minutes. The plane fell about 10,000 feet during the time it took to restart, but it managed to land safely in Anchorage, Alaska. Damage to

FIGURE 8.21 Volcanic ash on roofs Ash on buildings may increase the load on walls by several tons. Shown here are buildings that collapsed and burned from hot ash and lava during an eruption in Iceland in 1973. *(FLPA/Alamy)*

the aircraft was about $80 million.[6] Since the Alaska incident, Federal Aviation Administration (FAA) guidelines limit air traffic near volcanic ash clouds. In April 2010, an ash plume rising 9.5 km (6 mi) into the atmosphere above the erupting Icelandic volcano Eyjafjallajokull forced the shutdown of the airspace above a large region, including the United Kingdom, Ireland, Sweden, Norway, and other parts of northern Europe. The shutdown was the largest aerial closure in Europe in the past 70 years. About 95,000 flights were canceled because it was feared that the ash could damage aircraft and perhaps cause engine failure. As a result, several hundred thousand passengers were stranded in airports, at a cost to the airline industry of more than $1 billion during a single 1-week period[11,12]

Ash Flows. Ash flows, or nueé ardentes, may be as hot as 800 degrees Celsius and move as fast as 200 km per hour (125 mi per hour) down the sides of a volcano, incinerating everything in their path. They can be catastrophic if a populated area is in the path of the flow; fortunately, they seldom occur in populated areas. A tragic example occurred in 1902 on the West Indian island of Martinique. On the morning of May 8, a flow of hot, glowing ash, steam, and other gases roared down Mt. Pelée and through the town of St. Pierre, killing 30,000 people. A jailed prisoner was one of only two survivors, and he was severely burned and horribly scarred. Reportedly, he spent the rest of his life touring circus sideshows as the "Prisoner of St. Pierre." Flows like these have occurred on volcanoes of the Pacific Northwest and Japan in the past and can be expected in the future.

Poisonous Gases

A number of gases, including water vapor (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S), are emitted during volcanic activity. Water and carbon dioxide make up more than 90 percent of all emitted gases. Toxic concentrations of hazardous volcanic gases rarely reach populated areas. A notable tragic exception occurred in 1986 in Lake Nyos, Cameroon, West Africa. Lake Nyos is located in a 200 m (656 ft)-deep crater on a dormant volcano; without any warning other than an audible rumbling, the seemingly dormant volcano released a dense cloud of gas, consisting primarily of carbon dioxide. Carbon dioxide is a colorless, odorless gas that is heavier than air. The gas cloud flowed 10 km (6.2 mi) down the volcano along a valley, hugging the ground and suffocating 1,700 people and 3,000 cattle (**Figure 8.22a,b**).[4]

Since 1986, carbon dioxide gas has continued to accumulate in the bottom of the lake, and another release could occur at any time. Although the lake area was to remain closed to all people but scientists studying the hazard, thousands of people are returning to farm the land. Scientists have installed an alarm system at the lake that will sound if carbon dioxide levels become high. They have also installed a pipe from the lake bottom to a degassing fountain on the surface of the lake (Figure 8.22c) that allows the carbon dioxide gas to escape slowly into the atmosphere. The hazard is being slowly reduced as the single degassing fountain is now releasing a little more carbon dioxide gas than is naturally seeping into the lake. At least five additional pipes with degassing fountains will be necessary to adequately reduce the hazard.

Sulfur dioxide can react in the atmosphere to produce acid rain downwind of an eruption. Toxic concentrations of some chemicals emitted as gases may be absorbed by volcanic ash that falls onto the land. Eventually, the acid rain and toxic ash are incorporated into the soil and into plants eaten by people and livestock. For example, fluorine is erupted as hydrofluoric acid; it can be absorbed by volcanic ash and can be leached into water supplies.[3]

In Japan, volcanoes are monitored to detect the release of poisonous gases, such as hydrogen sulfide. When releases are detected, sirens are sounded to advise people to evacuate to high ground to escape the gas.

Volcanoes can also produce a type of smog known as *vog* (volcanic material, *v*, and fog, *og*). For example, emissions of sulfur dioxide and other volcanic gases from Kilauea in Hawaii have continuously occurred since 1986. At times, these gases have traveled downwind and chemically interacted with oxygen and moisture in the atmosphere to produce vog conditions mixed with acid rain. At times, southeastern areas of Hawaii were blanketed with thick acidic haze, and health warnings were issued. The vog is potentially hazardous to both people and other living things, and adverse health effects are being evaluated in Hawaii.[13,14] Small acidic aerosol

FIGURE 8.22 **Poisonous gas from dormant volcano** (a) In 1986, Lake Nyos released immense volumes of carbon dioxide. *(T. Oban/Sygma/Corbis)* (b) The gas killed, by asphyxiation, about 1,700 people and 3,000 cattle. *(Peter Turnley/Corbis)* (c) Gas being released with a degassing fountain in 2001. *(University of Savoie)*

particulates and sulfur dioxide concentrations like those in vog can penetrate deep within human lungs and are known to induce asthma attacks and cause other respiratory problems. Atmospheric concentrations of sulfur dioxide emitted from Kilauea, at times, far exceed air quality standards (see Chapter 19). Residents and visitors have reported a variety of symptoms when exposed to vog, including breathing difficulties, headaches, sore throats, watery eyes, and flulike symptoms. In 1988, acid rain in the Kona district captured from rooftop rainwater-catchment systems produced lead-contaminated water in 40 percent of homes. The lead is leached by acid rain from roofing and plumbing materials. Some residents, when tested, were found to have an elevated concentration of lead in their blood, presumably from drinking the water.[14]

Debris Flows and Mudflows

The most serious secondary effects of volcanic activity are **debris flows** and **mudflows**, known collectively by their Indonesian name **lahars**. Lahars are produced when a large volume of loose volcanic ash and other ejecta becomes saturated with water and becomes unstable, allowing it to suddenly move downslope (see Figure 8.2). The distinction between a debris flow and a mudflow depends upon the dominant size of the particles. In debris flows, more than 50 percent of the particles are coarser than sand, 2 mm (0.08 in.) in diameter. We will discuss landslides in detail in Chapter 10.

Debris Flows. Research completed at several volcanoes suggests that even relatively small eruptions of hot volcanic material may quickly melt

large volumes of snow and ice. The copious amounts of melted water produce floods; a flood may erode the slope of the volcano and incorporate sediment, such as volcanic ash and other material, forming debris flows. Volcanic debris flows are fast-moving mixtures of sediment, including blocks of rock and water, with the general consistency of wet concrete. Debris flows can travel many kilometers down valleys from the flanks of the volcano where they were produced.[9] For example, a pyroclastic flow that erupted from Alaska's Mt. Redoubt volcano early in 1990 rapidly melted snow and ice while moving across Drift Glacier. Voluminous amounts of water and sediment produced a debris flow that quickly moved down the valley, with a discharge comparable to that of the Mississippi River at flood stage. Fortunately, the event was in an isolated area, so no lives were lost.[3]

Mudflows. Gigantic mudflows have originated on the flanks of volcanoes in the Pacific Northwest.[8] A mudflow that is composed mostly of volcanic ash is often called a *lahar*. The paths of two ancient mudflows originating on Mt. Rainier are shown in **Figure 8.23**.

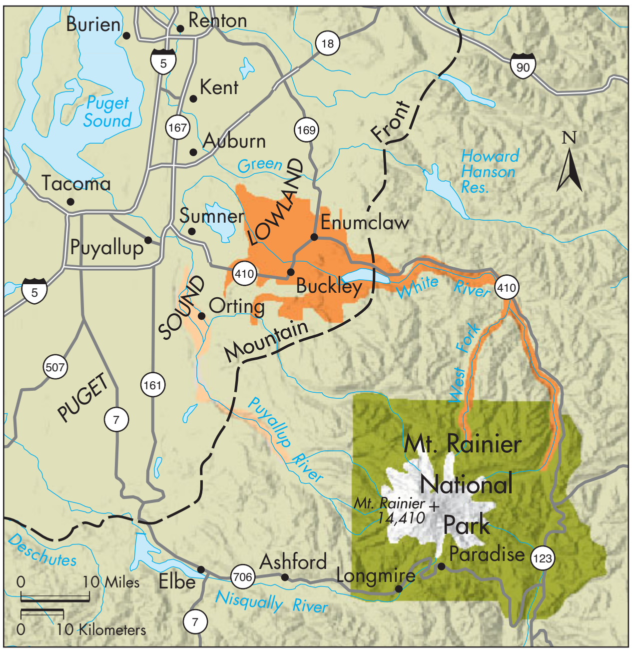


FIGURE 8.23 Mudflow Map of Mt. Rainier and vicinity showing the extent of the Osceola mudflow in the White River valley (orange) and the Electron mudflow (beige) in the Puyallup River valley. *(From Crandell, D. R., and Mullineaux, D. R., U.S. Geological Survey Bulletin 1238)*

Deposits of the Osceola mudflow are 5,000 years old. This mudflow moved more than 80 km (50 mi) from the volcano and involved more than 1.9 km^3 (0.45 mi^3) of debris, equivalent to 13 km^2 (5 mi^2) piled to a depth of more than 150 m (492 ft). Deposits of the younger, 500-year-old Electron mudflow reached about 56 km (35 mi) from the volcano.

Hundreds of thousands of people now live on the area covered by these old flows, and there is no guarantee that similar flows will not occur again. **Figure 8.24** shows the potential risk of mudflows, lava flows, and pyroclastic debris accumulation for Mt. Rainier. Someone in the valley facing the advancing front of such a flow would describe it as a wall of mud a few meters high, moving at about 30 to 50 km per hour (20 to 30 mi per hour). This observer would first see the flow at a distance of about 1.6 km (around 1 mi) and would need a car headed in the right direction toward high ground to escape being buried alive.[9]

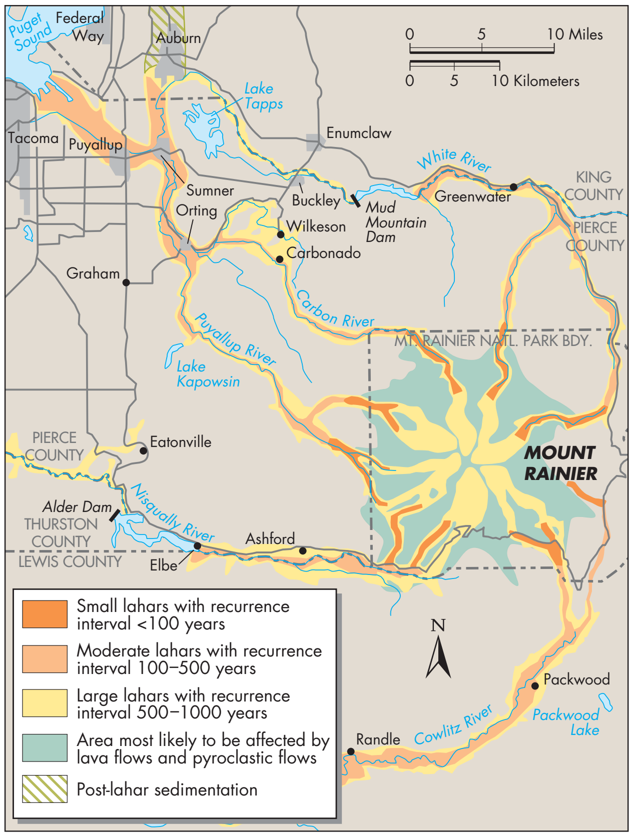
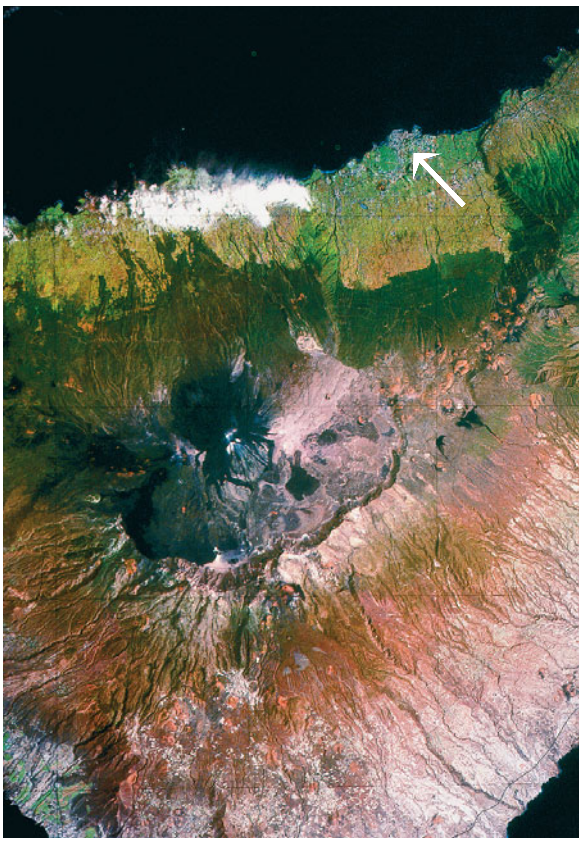


FIGURE 8.24 Mudflow hazard potential Map of Mt. Rainier and vicinity showing potential hazards from lahars, lava flows, and pyroclastic flows. *(Hoblitt and others. 1998. U.S. Geological Survey Open File Report 98-428)*

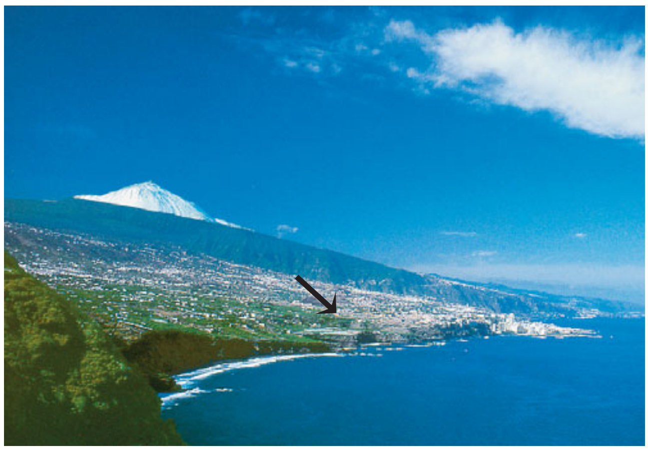
The U.S. Geological Survey has developed an automated, solar-powered lahar-detection system for several volcanoes in the United States (e.g., Mt. Rainier), Indonesia, the Philippines, Mexico, and Japan. Detectors (i.e., acoustic-flow monitors) that sense ground vibrations from a moving lahar can warn that a flow is moving down the valley. The system replaces visual sightings or cameras that are not reliable in bad weather or at night and require continued personal attention. Dangerous lahars can occur quickly, with little warning. The important thing is to know when to evacuate. If the lahar-detection system sounds an alarm that a lahar is approaching, the warning is issued with sufficient time to evacuate to safe (higher) ground.[15]

What may be the largest active landslides on Earth are located in Hawaii. Presently, these landslides are slow moving (approximately 10 cm [4 in.] per year). They can be up to 100 km (62 mi) wide, 10 km (6.2 mi) thick, and 20 km (12.4 mi) long and extend from a volcanic rift zone on land to an endpoint beneath the sea. These slow-moving landslides contain blocks of rock the size of Manhattan Island. The fear is that they might, as they have in the past, become giant, fast-moving submarine debris avalanches, generating huge tsunamis that deposit marine debris hundreds of meters above sea level at nearby islands and cause catastrophic damage around the Pacific Basin. Fortunately, such high-magnitude events apparently happen only every 100,000 years or so.[4]

Other huge volcano-related landslides and debris avalanches have been documented in the Canary Islands, located in the Atlantic Ocean off the western coast of Africa. On Tenerife, the largest island, six huge landslides have occurred during the past several million years (**Figure 8.25**). The most recent event occurred less than 150,000 years ago. Mt. Teide, with an elevation of 3.7 km (2.3 mi), is within the now-collapsed Cañada Caldera.[16,17] The landslides have produced large linear valleys, the largest of which is Orotova Valley, the site of the city of Puerto de la Cruz, which is a major coastal tourist destination and retirement center for Europeans. The youngest valley is Icod (Figure 8.25). The total volume of the slide deposits exceeds 1,000 km^3



(a)



(b)

FIGURE 8.25 Giant landslide on volcano
(a) Part of the island of Tenerife, Canary Islands. Labeled are the collapsed Cañada Caldera and Mt. Teide (elevation 3.7 km [12,100 ft]). *(Espagna Instituto Geografico Nacional)* In both images, the arrow points to the landslide. (b) Landslide in the valley of Orotova. The city shown is Puerto de la Cruz. *(Jose Barea/Espagna Instituto Geografico Nacional)*

(240 mi^3). The offshore seafloor north of Tenerife is covered by 5,500 km^2 (2,150 mi^2) of landslide deposits, an area of more than twice the land surface of the island.[18]

There is concern that a future landslide from Tenerife or La Palma, another of the Canary Islands, would cause a huge tsunami known as a *megatsunami*. Waves with heights exceeding 100 m are possible. They would cause catastrophic damage to the eastern coast of the United States, including the city of New York. The possibility of future huge landslides is unknown, but their occurrence cannot be ruled out.

8.7 Two Case Histories

Mt. Pinatubo

On June 15 and 16, 1991, the second largest volcanic eruption of the twentieth century occurred at Mt. Pinatubo on Luzon Island in the Philippines (**Figure 8.26**). The combined effects of ash fall, debris flows, mudflows, and a typhoon resulted in the deaths of about 300 people. Most deaths were due to the collapse of buildings as heavy, wet volcanic ash—resulting from the simultaneous arrival of Typhoon Yunya—accumulated on roofs to thicknesses of 30 cm (12 in.) as far as 40 km (25 mi) from the volcano.[2] Evacuation of 250,000 people from villages and a U.S. military base within a radius of 30 km (19 mi) from the summit saved thousands of lives.[4] Teams of scientists educated local people and authorities by talking to them and showing them videos of volcanic eruptions and their potential hazards. Their efforts convinced local officials to order the evacuations and the people who were at risk to comply.[19]

FIGURE 8.26 Evacuation Thousands of people were evacuated, including more than 1,000 from U.S. Clark Air Base, during this large ash eruption and explosion of Mt. Pinatubo in the Philippines in June 1991. *(Carlo Cortes/Reuters/Corbis)*

The tremendous explosions at Pinatubo sent a cloud of ash 400 km (250 mi) wide to elevations of 34 km (21 mi).[4] As with similar past events of this magnitude, the aerosol cloud of ash, including sulfur dioxide, remained in the atmosphere for more than a year. The ash particles and sulfur dioxide scattered incoming sunlight and slightly cooled the global climate during the year following the eruptions.[2,19]

The 1991 success of saving lives during the Mt. Pinatubo eruptions stands in stark contrast to the 1985 eruption of Nevado del Ruiz (see Chapter 5). In Armero, a volcanic hazard became a catastrophe that resulted in part from a series of human errors. It was not a huge eruption or a case of bad luck. Rather, it resulted because the science of the hazard was not effectively communicated to people and officials in the area. Nevado del Ruiz was a tragedy that could have and should have been avoided.

Mount St. Helens

The May 18, 1980, eruption of Mount St. Helens in the southwestern corner of Washington (**Figure 8.27**) exemplifies the many types of volcanic events expected from a Cascade volcano. The eruption, like many other natural events, was unique and complex, making generalizations somewhat difficult. Nevertheless, we have learned a great deal from Mount St. Helens, and the story is not yet complete.

Mount St. Helens awoke in March 1980, after 120 years of dormancy, with seismic activity and small explosions as groundwater came into contact

(a)

(b)

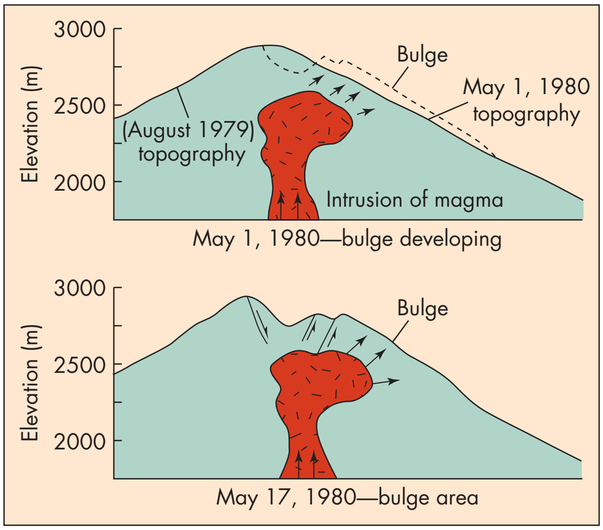
(c)

FIGURE 8.27 Mount St. Helens before and after (a) Location of Mount St. Helens. (b) Mount St. Helens before and (c) after the May 18, 1980, eruption. As a result of the eruption, much of the northern side of the volcano was blown away, and the altitude of the summit was reduced by approximately 450 m (1,476 ft). *(Photo [b] by Bruce Spainhower/Washington State Tourism Development Division. Photo [c] by Harry Glicken/Washington State Tourism Development Division)*

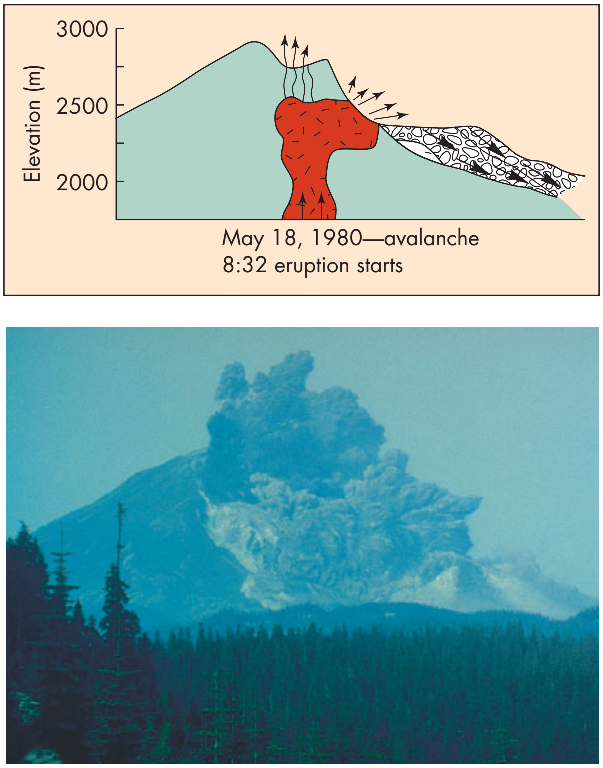
with hot rock. By May 1, a prominent bulge on the northern flank of the mountain could be clearly observed and grew at a rate of about 1.5 m per day (5 ft per day) (**Figure 8.28a**). At 8:32 A.M. on May 18, 1980, a M 5.1 earthquake that was registered on the volcano triggered a large landslide/debris avalanche (approximately 2.3 km^3 [0.6 mi^3]) that involved the entire bulge area (Figure 8.28b). The avalanche shot down the north flank of the mountain, displacing water in nearby Spirit Lake; struck and overrode a ridge 8 km (5 mi) to the north; and then made an abrupt turn, moving 18 km (11 mi) down the Toutle River.

Seconds after the failure of the bulge, Mount St. Helens erupted with a lateral blast directly from the area that the bulge had occupied (Figure 8.28c). The blast moved at speeds up to 1,000 km per hour (621 mi per hour) to distances of nearly 30 km (19 mi) from its source. The blast devastated an area of about 600 km^2 (232 mi^2).[20,21] The areas of the debris avalanche, blasted-down timber, scorched timber, pyroclastic flows, and mudflows are shown in **Figure 8.29a** (page 277).

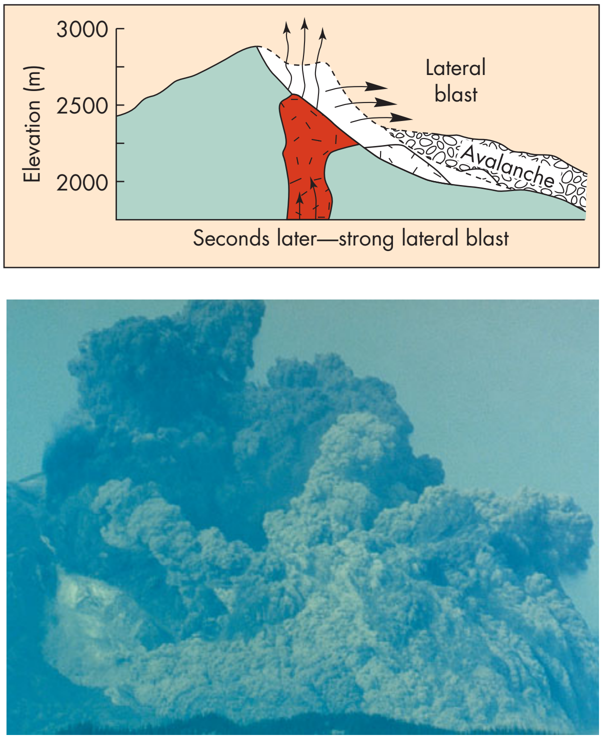
About an hour after the lateral blast, a large vertical cloud had risen quickly to an altitude of approximately 19 km (12 mi) (Figure 8.28d). Eruption of the vertical column continued for more than 9 hours, and large volumes of volcanic ash fell on a wide area of Washington, northern Idaho, and western and central Montana. During the 9 hours of eruption, several ash flows swept down the northern slope of the volcano. The total amount of volcanic ash ejected



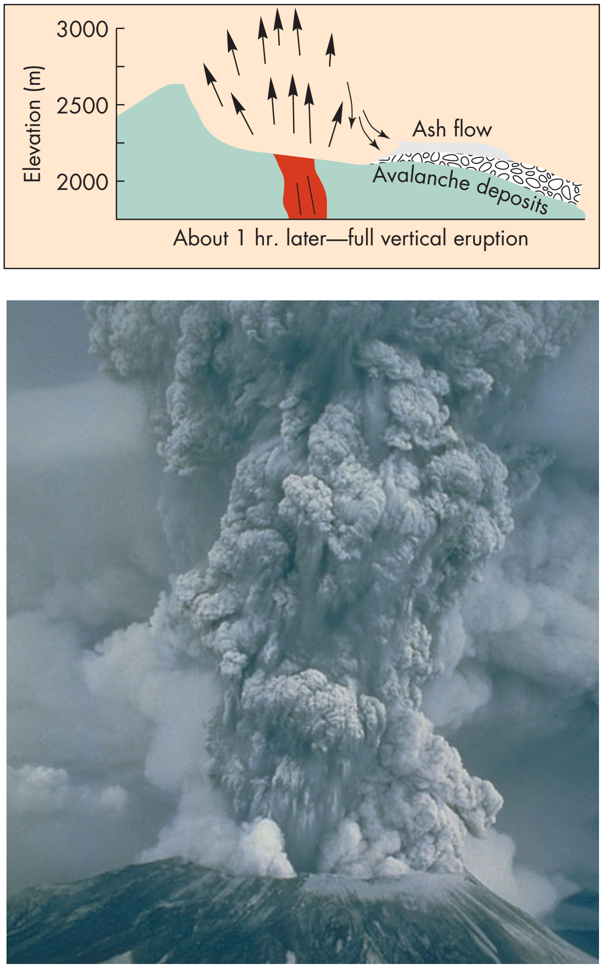
(a) Before eruption May 1 to 17, 1980



(b) Eruption starts May 18,1980



(c) Seconds after eruption starts



(d) About an hour after eruption starts

FIGURE 8.28 Mount St. Helens erupts Diagrams and photographs showing the sequence of events for the May 18, 1980, eruption of Mount St. Helens. *(Photographs [a], [b], and [c] © 1980 by Keith Ronnholm, the Geophysics Program, University of Washington, Seattle. Photograph [d] from Roger Werth/Woodfin Camp and Associates. Drawings inspired from lecture by James Moore, U.S. Geological Survey)*

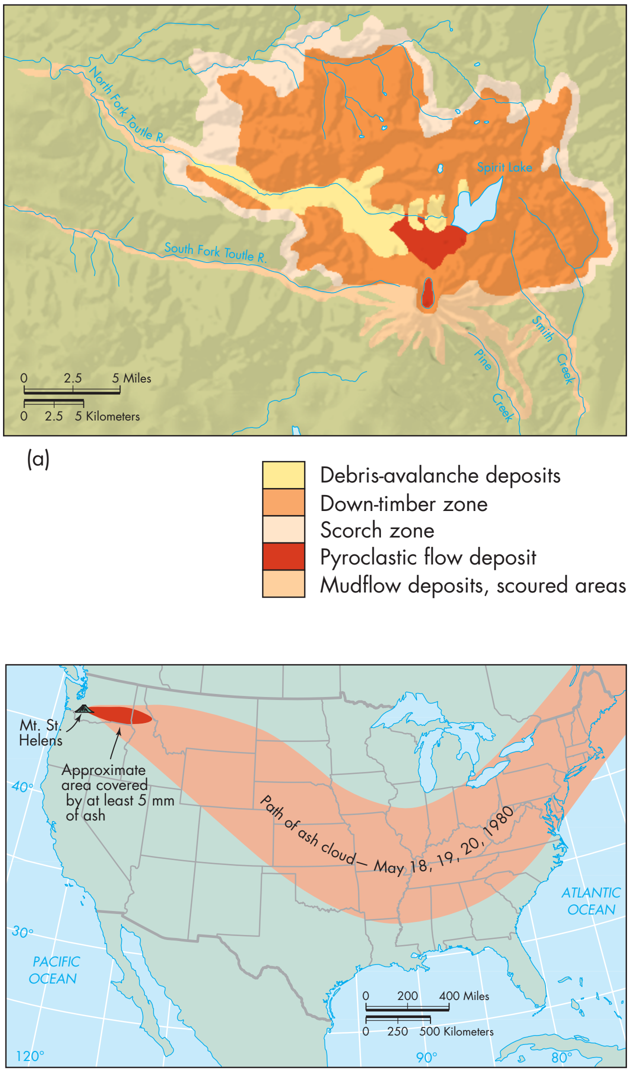


FIGURE 8.29 Debris avalanche and ash cloud (a) Mount St. Helens debris-avalanche deposits, zones of timber blown down or scorched, mudflows, and pyroclastic flow deposits associated with the May 18, 1980, eruption. (b) Path of the ash cloud from the 1980 eruption. *(Data from various U.S. Geological Survey publications)*

FIGURE 8.30 Barren landscape produced by eruption The desolate, barren landscape shown here was produced by the May 18, 1980, eruption of Mount St. Helens. The debris avalanche/debris flow that moved down the Toutle River valley is shown here from the center left of the photograph to the lower-right corner. The entire valley is full of debris. The surface of the deposit is hummocky, characterized by a scattering of large blocks of volcanic debris. *(University of Washington Libraries)*

was about 1 km^3 (0.24 mi^3), and a large cloud of ash moved over the United States, reaching as far east as New England (Figure 8.29b). The entire northern slope of the volcano, which is the upper part of the north fork of the Toutle River basin, was devastated. Forested slopes were transformed into a gray, hummocky, or hilly, landscape consisting of volcanic ash, rocks, blocks of melting glacial ice, narrow gullies, and hot steaming pits (Figure 8.30).[21]

The first of several mudflows consisted of a mixture of water, volcanic ash, rock, and organic debris, such as logs, and occurred minutes after the start of the eruption. The flows and accompanying floods raced down the valleys of the north and south forks of the Toutle River at estimated speeds of 29 to 55 km per hour (18 to 35 mi per hour), threatening the lives of people camped along the river.[21]

On the morning of May 18, 1980, two young people on a fishing trip on the Toutle River were sleeping about 36 km (22 mi) downstream from Spirit Lake. They were awakened by a loud rumbling noise from the river, which was covered by felled trees. They attempted to run to their car, but water from the rising river poured over the road, preventing their escape. A mass of mud then crashed through the forest toward the car, and the couple climbed onto the car roof to escape the mud. They were safe only momentarily, however, as the mud pushed the

(a)

(b)

FIGURE 8.31 The years of recovery (a) The eruption of May 18, 1980, of Mount St. Helens produced a barren landscape. *(University of Washington Libraries)* (b) It is recovering, as illustrated by the flowering lupine 10 years later, in July 1990. *(Gary Braasch/Woodfin Camp & Associates)*

vehicle over the bank and into the river. Leaping off the roof, they fell into the river, which was by now a rolling mass of mud, logs, collapsed train trestles, and other debris. The water also was increasing in temperature. One of the young people got trapped between logs and disappeared several times beneath the flow but was lucky enough to emerge again. The two were carried downstream for approximately 1.5 km (0.9 mi) before another family of campers spotted and rescued them.

When the volcano could be viewed again after the eruption, its maximum altitude had been reduced by about 450 m (1,476 ft): The original symmetrical mountain was now a huge, steep-walled amphitheater facing northward, and Spirit Lake (lower Figure 8.27b) was filled by deposits (Figure 8.27c). The debris avalanche, lateral blast, pyroclastic flows, and mudflows devastated an area of nearly 400 km^2 (154 mi^2), killing 54 people. More than 100 homes were destroyed by the flooding, and approximately 800 million board-feet of timber were flattened by the blast (Figure 8.29a). A board-foot is a board of 1 ft^2 that is 1 in. thick. The total damage was estimated to exceed $1 billion.

After the catastrophic eruption of Mount St. Helens, an extensive program was established to monitor volcanic activity. The construction by lava flows of a dome within the crater produced by the May 18, 1980, eruption is carefully monitored. During the first 3 years following the eruption, at least 11 smaller eruptions occurred. These smaller eruptions contributed to the building of the lava dome to a height of approximately 250 m (820 ft). In each of these eruptions, lava was extruded near the top of the dome and slowly flowed toward the base. Monitoring the growth of the dome and the deformation of the crater floor, along with such other techniques as monitoring the gases emitted, was useful in predicting eruptions. Each event added a few million cubic meters to the size of the dome.[22] By 2000, 20 years after the main eruption, life had returned to the mountain, and its surrounding area was in many places green once more (**Figure 8.31**).[20] However, the hummocky landscape from the landslide deposits is still prominent, a reminder of the catastrophic event of 1980. Mount St. Helens has a visitors' center and is now a tourist attraction that has attracted more than 1 million visitors.[23]

8.8 Forecasting Volcanic Activity

A "forecast" for a volcanic eruption is a probabilistic statement concerning the time, place, and character of an eruption before it occurs. It is analogous to forecasting the weather and is not as precise a statement as a prediction.[4] Forecasting volcanic eruptions is a major component of the goal of reducing volcanic hazards.

It is unlikely that we will be able to forecast the majority of volcanic activity accurately in the near future, but valuable information is being gathered about phenomena that occur before eruptions.

One problem is that most forecasting techniques require experience with actual eruptions before the mechanism is understood. Thus, we are better able to predict eruptions in the Hawaiian Islands than elsewhere because we have had so much experience there.

The methods of forecasting volcanic eruptions include:

- Monitoring seismic activity
- Monitoring thermal, magnetic, and hydrologic conditions
- Topographically monitoring tilting or swelling of the volcano
- Monitoring volcanic gas emissions
- Studying the geologic history of a particular volcano or volcanic center[3,19,24]

Seismic Activity

Our experience with volcanoes, such as Mount St. Helens and those on the big island of Hawaii, suggests that earthquakes often provide the earliest warning of an impending volcanic eruption. In the case of Mount St. Helens, earthquake activity started in mid-March, before the eruption in May. Activity began suddenly, with near-continuous shallow seismicity. Unfortunately, there was no increase in earthquakes immediately before the May 18 event. In Hawaii, earthquakes have been used to monitor the movement of magma as it approaches the surface.

Several months before the 1991 Mt. Pinatubo eruptions, small steam explosions and earthquakes began.[3] Mt. Pinatubo (present elevation 1,700 m [5,578 ft]) was an eroded ridge, and, as a result, did not have the classic shape of a volcano. Furthermore, it had not erupted in 500 years; most of the people living near it did not even know it was a volcano! Scientists began monitoring earthquake activity and studying past volcanic activity, which was determined to be explosive. Earthquakes increased in number and magnitude before the catastrophic eruption, migrating from deep beneath the volcano to shallow depths beneath the summit.[4]

Geophysicists have proposed a generalized model for seismic activity that may help in predicting eruptions.[25] This model is for explosive composite volcanoes, such as those in the Cascade Mountains, which may awaken after an extended period of inactivity (Figure 8.32). In a reawakening volcano, the magma must fracture and break previously solidified igneous rock above the magma chamber in order to work its way to the surface. Several weeks before reawakening, increasing pressure creates numerous fractures in the plugged volcanic conduit above the chamber. At first, the increase in seismic events will be very gradual, and a seismologist may need 10 days or so to confidently recognize an accelerating trend toward an eruption (Figure 8.32). However, once the trend has been recognized, there will be several days before the eruption occurs. Unfortunately, this short warning time may be insufficient for a large-scale evacuation. Thus, to forecast eruptions, it may be best to use seismic activity in concert with other eruption precursors discussed below. It is fortunate that, in contrast to earthquakes, volcanic eruptions always provide warning signs.[26]

Thermal, Magnetic, and Hydrologic Monitoring

Monitoring of volcanoes is based on the fact that, before an eruption, a large volume of magma moves up into some sort of holding reservoir beneath the volcano. The hot material changes the local magnetic, thermal, hydrologic, and geochemical conditions. As the surrounding rocks heat, the rise in temperature of the surficial rock may be detected by remote sensing or infrared aerial photography. Increased heat may melt snowfields or glaciers; thus, periodic remote sensing of a volcanic chain may detect new hot points that could indicate potential volcanic activity. This method was used with some success at Mount St. Helens before the main eruption on May 18, 1980.

When older volcanic rocks are heated by new magma, magnetic properties, originally imprinted when the rocks cooled and crystallized, may change. These changes can be detailed by ground or aerial monitoring of the magnetic properties of the rocks that the volcano is composed of.[3,24]

Topographic Monitoring

Monitoring topographic changes and seismic behavior of volcanoes has been useful in forecasting some volcanic eruptions. The Hawaiian volcanoes, especially Kilauea, have supplied most of the data. The summit of Kilauea tilts and swells before an eruption and

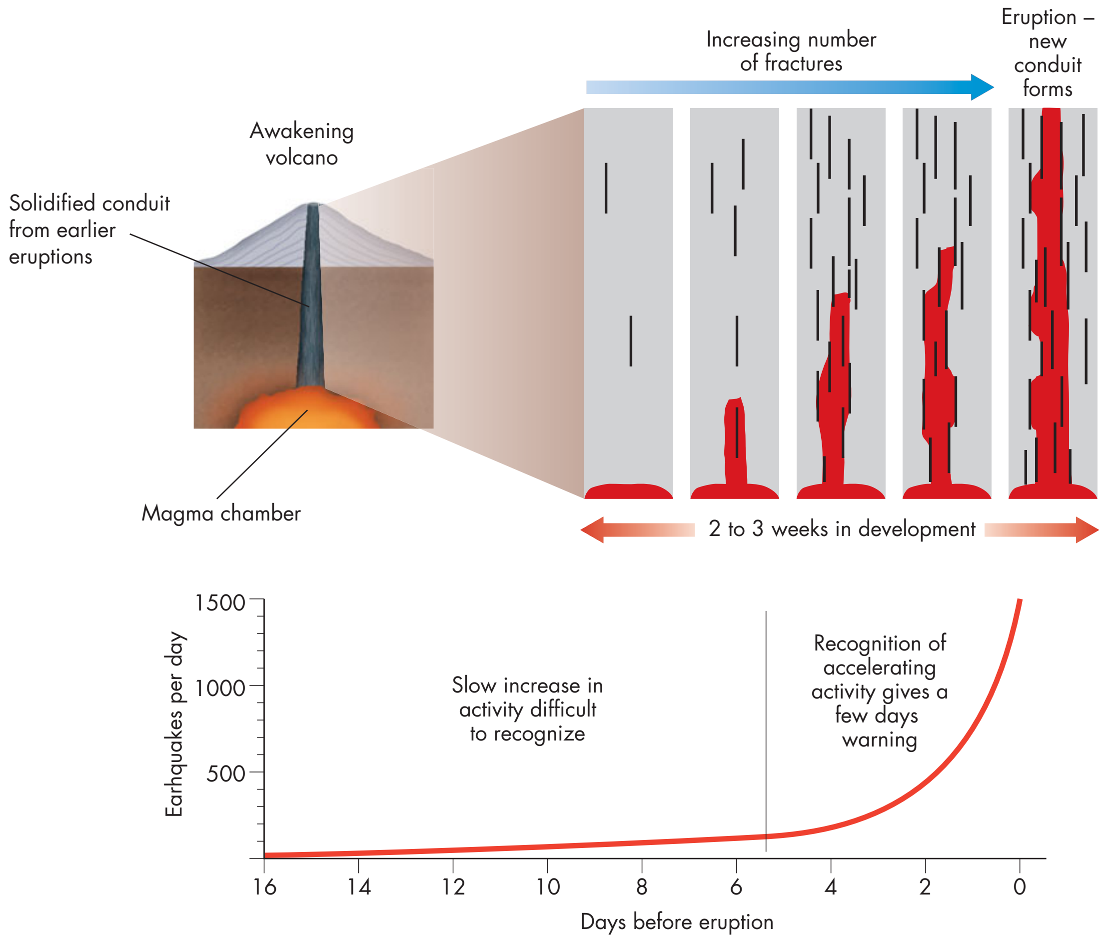
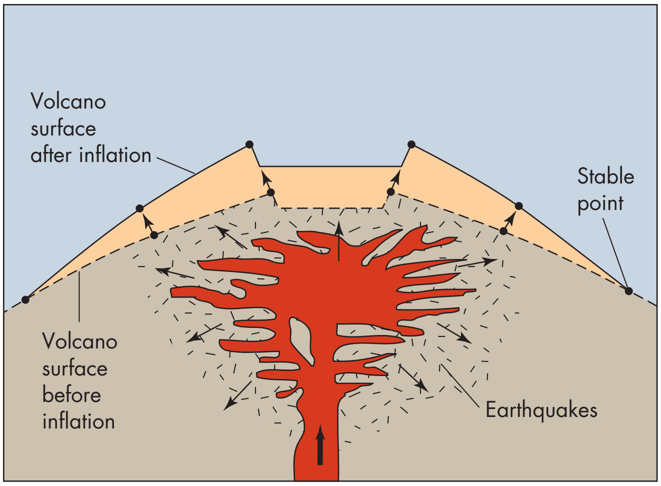


FIGURE 8.32 A volcano reawakens Increased seismic activity is a good indicator of a forthcoming volcanic eruption. As a dormant volcano reawakens, rising magma fractures rock above. At first, the fracturing slowly increases the rate of seismic activity; then both the fracturing and seismic activity accelerate a few days prior to an eruption. *(Modified after Kilburn, C. R. J., and Sammonds, P. R. 2005. Maximum warning times for imminent volcanic eruptions.* Geophysical Research Letters *32:L24313, doi 10.1029/2005GL024184*

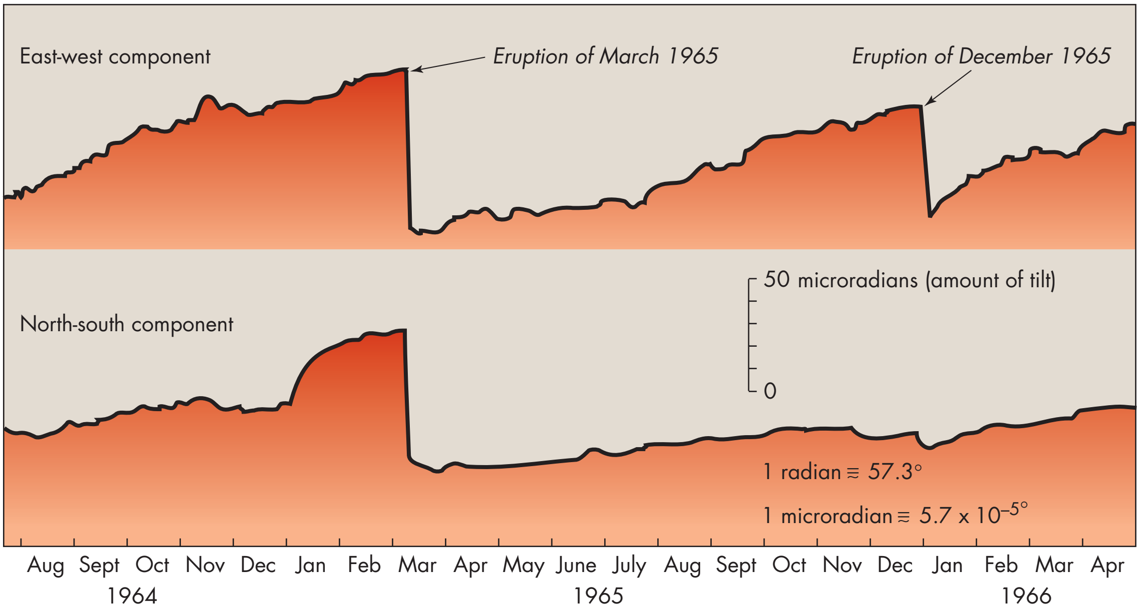
subsides during the actual outbreak (**Figure 8.33**). Kilauea also undergoes earthquake swarms that reflect moving subsurface magma and an imminent eruption. The tilting of the summit in conjunction with the earthquake swarms was used to predict a volcanic eruption in the vicinity of the farming community of Kapoho on the flank of the volcano, 45 km (28 mi) from the summit. As a result, the inhabitants were evacuated before the event, in which lava overran and eventually destroyed most of the village.[27] Because of the characteristic swelling and earthquake activity before eruptions, scientists expect the Hawaiian volcanoes to continue to be more predictable than others. Monitoring of ground movements, such as tilting, swelling, opening of cracks, or changes in the water level of lakes on or near a volcano, has become a useful tool for recognizing change that might indicate a coming eruption.[3] Today, satellite-based radar and a network of global positioning system (GPS) receivers can be used to monitor change in volcanoes, including surface deformation, without sending people into a hazardous area.[20]

Monitoring Volcanic Gas Emissions

The primary objective of monitoring volcanic gas emissions is to recognize changes in the chemical composition of the gases. Changes in both gas composition—that is, the relative amounts of gases, such as steam, carbon dioxide, and sulfur dioxide—and gas emission rates are thought to be correlated with changes in subsurface volcanic processes. These factors may indicate movement of magma toward the surface. This technique was



(a)



(b)

FIGURE 8.33 Inflation and tilting before eruption (a) Idealized diagram of Kilauea, illustrating inflation and surface tilting accompanied by earthquakes as magma moves up. *(U.S. Geological Survey Circular 1073, 1992)* (b) The actual data graph, showing the east–west component and the north–south component of ground tilt recorded from 1964 to 1966 on Kilauea Volcano, Hawaii. Notice the slow change in ground tilt before eruption and rapid subsidence during eruption. *(From Fiske, R. S., and Koyanagi, R. Y. 1968. U.S. Geological Survey Professional Paper 607)*

useful in studying eruptions at Mount St. Helens and Mt. Pinatubo. Two weeks before the explosive eruptions at Mt. Pinatubo, the emissions of sulfur dioxide increased by a factor of about 10.[3]

Geologic History

Understanding the geologic history of a volcano or volcanic system is useful in predicting the types of eruptions likely to occur in the future. The primary tool used to establish the geologic history of a volcano is geologic mapping of volcanic rocks and deposits. Lava flows, volcanic mud flow deposits, pyroclastic deposits, and ash deposits are dated (for example dating wood buried in deposits using carbon-14) to determine when eruptions occurred in the past. These are the primary data necessary to produce maps depicting volcanic hazards at a particular site. Geologic mapping, in conjunction with the dating of volcanic deposits at Kilauea, Hawaii, led to the discovery that more than 90 percent of the land surface of the volcano has been covered by lava in only the past 1,500 years. The town of Kalapana, destroyed by lava flows in 1990, might never have been built if this information had been known before development because the risk might have been thought too great.

TABLE 8.3 Volcanic Activity Color Coded Alert Notification System.

GREEN Normal	Volcano is in typical background, non-eruptive state or, *after a change from a higher level,* volcanic activity has ceased and volcano has returned to noneruptive background state.
YELLOW Advisory	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE Watch	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway with no or minor volcanic-ash emissions (ash-plume height specific, if possible).
RED Warning	Eruption is imminent with significant emmission of volcanic ash into the atmosphere likely **OR** eruption is underway or suspected with significant emission of volcanic ash into the atmosphere (ash-plume height specified, if possible).

Modified from U.S. Geological Survey 2007. http://volcanoes.usgs.gov.

The real value of geologic mapping and dating of volcanic events is that they allow development of hazard maps to assist in land-use planning and preparation for future eruptions.[3] Such maps are now available for a number of volcanoes around the world.

Volcanic Alert or Warning

At what point should the public be alerted or warned that a volcanic eruption may occur? This is an important question being addressed by volcanologists. At present, there is no standard code, but one being used with various modifications has been developed by the U.S. Geological Survey. The system is color coded by condition; each color—green, yellow, orange, and red—denotes increasing concern. (Table 8.3). The color-coded system is a good start; however, the hard questions remain: When should evacuation begin? When is it safe for people to return? Evacuation is definitely necessary before condition red, but when, during conditions yellow or orange, should it begin?

8.9 Adjustment to and Perception of the Volcanic Hazard

Apart from the psychological adjustment to losses, the primary human adjustment to volcanic activity is evacuation. A notable exception is the previously discussed decision of the people on the island of Heimaey to successfully fight an eruption by hydraulically chilling the lava. Information concerning how people perceive the volcanic hazard is limited. People live near volcanoes for a variety of reasons, including: (1) They were born there, and, in the case of some islands such as the Canary Islands, all land on the island is volcanic; (2) the land is fertile and good for farming; (3) people are optimistic and believe an eruption is unlikely; and (4) they do not have any choice as to where they live—for example, they may be limited by economics. One study of perception evaluated volcanic activity in Hawaii and found that a person's age and length of residence near a volcanic hazard are significant factors in a person's knowledge of volcanic activity and possible adjustments.[28] One reason the evacuation of 60,000 people before the 1991 eruption of Mt. Pinatubo was successful was that the government had provided a program to educate people concerning the dangers from violent ash eruptions with debris flows. A video depicting these events was widely shown in the area before the eruption, and it helped convince local officials and residents that they faced a real and immediate threat.[4]

The science of volcanoes is becoming well known. However, good science is not sufficient. Probably the greatest payoff in terms of reducing volcanic hazards in the future will come from an increased understanding of human and societal issues that come up during an emerging potential **volcanic crisis**—that is, a situation in which the science

suggests that a volcanic eruption is likely in the near future. The development of improved communication between scientists, emergency managers, educators, media, and private citizens is particularly important. The goal is to prevent a volcanic crisis from becoming a volcanic disaster or catastrophe.[20]

Making The Connection

Linking the Opening Case History About Mt. Unzen, Mt. Pinatubo, and Mount St. Helens to the Fundamental Concepts

Consider and discuss the following questions:

1. Compare the role of human population increase for the three eruptions with projected population increase in the next 50 years.
2. Compare the role of scientific information in understanding the three eruptions.
3. How is the study of volcanoes as part of Earth systems science helping us understand the risk from future eruptions?
4. How was each eruption perceived by people in the vicinity of the eruption?

Summary

Volcanic eruptions often occur in sparsely populated areas, but they have a high potential to produce catastrophes when they occur near populated areas. Volcanic activity is directly related to plate tectonics. Most volcanoes are located at plate boundaries, where magma is produced as spreading or sinking lithospheric plates interact with other Earth material. The "ring of fire" is a region surrounding most of the Pacific Ocean (Pacific plate) that contains about two-thirds of the world's volcanoes.

Lava is magma that has been extruded from a volcano; the activity of different types of volcanoes is partly determined by the differing silica content and viscosity of their lavas. Shield volcanoes occur at mid-ocean ridges, such as Iceland, and over mid-plate hot spots, such as the Hawaiian Islands. Their common rock type is basalt, and they are characterized by nonexplosive lava flows. Composite volcanoes occur at subduction zones, particularly around the Pacific Rim, for example, in the Pacific Northwest of the United States. They are composed largely of andesite rock and are characterized by explosive eruptions and lava flows. Volcanic domes occur inland of subduction zones; an example of a volcanic dome is Mt. Lassen, California. They are composed largely of rhyolite rock and are highly explosive.

Features of volcanoes include vents, craters, and calderas. Other features of volcanic areas are hot springs and geysers. Giant caldera-forming eruptions are violent, but rare, geologic events. After their explosive beginning, they often resurge and may present a volcanic hazard for a million years or longer. Recent uplift and earthquakes at the Long Valley caldera in California are reminders of the potential hazard.

Primary effects of volcanic activity include lava flows, pyroclastic hazards, and, occasionally, the emission of poisonous gases. Hydraulic chilling and the construction of walls have been used in attempts to control lava flows. These methods have had mixed success and require further evaluation. Pyroclastic hazards include volcanic ash falls, which may cover large areas with carpets of ash; ash flows, or hot avalanches, which move as fast as 100 km per hour down the side of a volcano; and lateral blasts, which can be very destructive. Secondary effects of volcanic activity include debris flows and mudflows, generated when melting snow and ice or precipitation mixes with volcanic ash. These flows can devastate an area many kilometers from the volcano. All of these effects have occurred in the recent history of the Cascade Range of the Pacific Northwest, and there is no reason to believe that they will not occur there in the future.

Sufficient monitoring of seismic activity; thermal, magnetic, and hydrologic properties; and topographic changes, combined with knowledge of the recent geologic history of volcanoes, may eventually result in reliable forecasting of volcanic activity. Forecasts of eruptions have been successful, particularly for Hawaiian volcanoes and Mt. Pinatubo in the Philippines. On a worldwide scale, however, it is unlikely that we will be able to accurately forecast most volcanic activity in the near future.

Apart from psychological adjustment to losses, the primary human adjustment to volcanic activity is evacuation. Perception of the volcanic hazard is apparently a function of age and length of residency near the hazard. Some people have little choice but to live near a volcano. Education plays an important role in informing people about the hazards of volcanoes.

The goal of reducing the volcanic hazard is focusing on human and societal issues through communication, with the objective of preventing a volcanic crisis from becoming a volcanic disaster or catastrophe.

Revisiting Fundamental Concepts

Human Population Growth
When humans live close to active volcanoes, the consequences can be catastrophic. Volcanic soil is generally rich, and population centers often develop in broad agricultural-based valleys downslope from volcanoes. In addition, large urban centers, including Seattle, Washington, and Mexico City, are uncomfortably close to active volcanoes. In some cases, such as island cities like Puerto de la Cruz on Tenerife, Canary Islands, the entire island is part of a large volcanic center. There is no alternative for the island people other than to live in a potentially hazardous area. As population centers and cities near volcanoes grow and attract more people in the next 100 years, the volcanic hazard will become more serious to millions of additional people.

Earth as a System Volcanoes are part of the internal system of Earth. Magma is generated at plate boundaries and hot spots that change position and progress only slowly over time periods of interest to people. However, when a volcano becomes active, there are important changes in the earthquakes it produces and the gases it releases as magma moves toward the surface. These changes alert us and help predict eruptions.

Hazardous Earth Processes, Risk Assessment, and Perceptions Volcanoes are one of our most violent natural hazards. Yet people living in the shadow of a volcano that has been dormant for a few hundred years may scarcely know it is there, and the potential threat of future eruptions may be unknown or not perceived as a threat. In areas with more frequent eruptions, such as Hawaii, people generally are aware of the risk, having lived with daily news reports of ongoing eruptions that may last for decades. In other words, if eruptions are frequent, people's perception of the hazard increases.

Scientific Knowledge and Values We have learned a great deal about how volcanoes function, the rocks they produce, and the hazards they present. However, values sometimes clash. For example, some people in the Hawaiian Islands view the volcanoes in a spiritual and religious light. Volcanic gases, magma, and lands are the breath and life of the volcanic goddess Pele, not to be used to produce geothermal energy or cover over with urban development. Removing bits of Pele's volcanic rocks from the island is believed to bring bad luck to the thief.

Key Terms

addition of volatiles (p. 254)
ash fall (p. 269)
ash flow (p. 269)
caldera eruption (p. 265)
cinder cone (p. 259)
composite volcano (p. 258)
decompression melting (p. 254)
debris flow/mudflow/lahar (p. 271)
lateral blast (p. 269)
lava (p. 253)
lava flow (p. 266)
magma (p. 251)
pyroclastic activity (p. 269)
shield volcano (p. 254)
volatiles (p. 254)
volcanic crisis (p. 282)
volcanic dome (p. 258)

Review Questions

1. From a hazards perspective, why is it important to know the type of a volcano?
2. What is viscosity, and what determines it?
3. List the major types of volcano and the type of magma associated with each.
4. List the major types of volcano and their eruption style. Why do they erupt the way they do?
5. What is the relationship between plate tectonics and volcanoes?
6. How do lava tubes help move magma far from the erupting vents?
7. What is the relationship between the Hawaiian Islands and the hot spot below the big island of Hawaii?
8. What is the origin of a geyser?
9. Why are caldera eruptions so dangerous?
10. List the primary and secondary effects of volcanic eruptions.
11. What are some of the methods that have been attempted to control lava flows?
12. Differentiate between ash falls, lateral blasts, and ash flows.
13. What are the major gases emitted in a volcanic eruption, and which are most hazardous?
14. How are volcanic eruptions able to produce gigantic mudflows?
15. What are some of the possible methods of forecasting volcanic eruption?

Critical Thinking Questions

1. While looking through some old boxes in your grandparents' home, you find a sample of volcanic rock collected by your great-grandfather. No one knows where it was collected. You take it to school, and your geology professor tells you that it is a sample of andesite. What might you tell your grandparents about the type of volcano from which it probably came, its geologic environment, and the type of volcanic activity that likely produced it?

2. In our discussion of adjustment to and perception of volcanic hazards, we established that people's perceptions and what they will do in case of an eruption are associated with both their proximity to the hazard and their knowledge of volcanic processes and necessary adjustments. With this association in mind, develop a public relations program that could alert people to a potential volcanic hazard. Keep in mind that the tragedy associated with the eruption of Nevado del Ruiz (see Chapter 5) was, in part, due to political and economic factors that influenced the apathetic attitude toward the hazard map prepared for that area. Some people were afraid that the hazard map would result in lower property values in some areas.

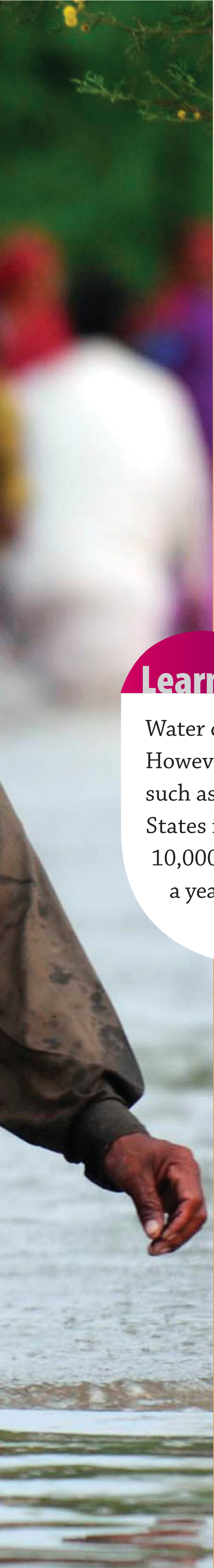
Companion Website

www.mygeoscienceplace.com

PEARSON mygeoscience place™ *Introduction to Environmental Geology, 5e* premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

People wading floodwaters in Pakistan 2010 flood. *(Rizwan Tabassum/AFP/Getty Images)*



9

Rivers and Flooding

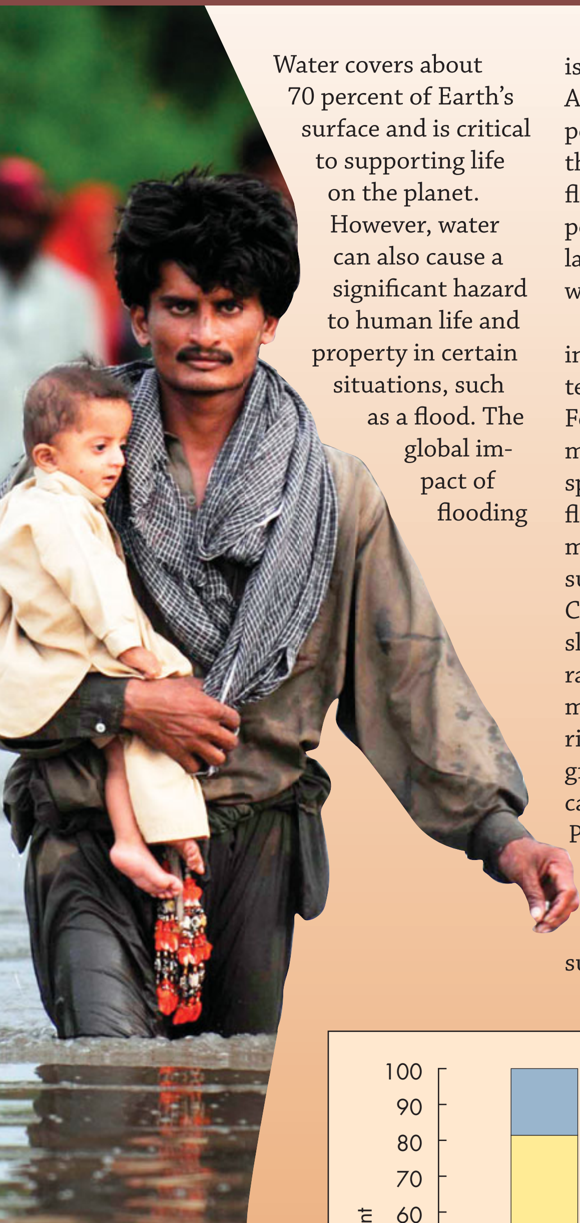
Learning Objectives

Water covers about 70 percent of Earth's surface and is critical to supporting life on the planet. However, water can also cause a significant hazard to human life and property in certain situations, such as a flood. Flooding is the most universally experienced natural hazard. Flooding in the United States is the most common and costly natural hazard we face. Floodwaters have killed more than 10,000 people in the United States since 1900, and property damage from flooding exceeds $5 billion a year. Flooding is a natural process that will remain a major hazard as long as people choose to live and work in flood-prone areas. In this chapter we focus on the following learning objectives:

- **Understand basic river processes**
- **Understand the nature and extent of the flood hazard**
- **Understand the effects of urbanization on flooding in small drainage basins**
- **Know the major adjustments to flooding and which are environmentally preferable**
- **Know the potential adverse environmental effects of channelization and the benefits of channel restoration**

Case History

Pakistan Floods of 2010 with Implications for the United States



Water covers about 70 percent of Earth's surface and is critical to supporting life on the planet. However, water can also cause a significant hazard to human life and property in certain situations, such as a flood. The global impact of flooding is shown in **Figure 9.1**. Notice that Asia suffers the greatest number of people killed or affected, along with the greatest economic loss, due to flooding. This reflects the high human population along rivers in Asia, and land use changes linked to a climate with intense precipitation.[1]

A *monsoon* refers to a seasonal shift in wind pattern and precipitation patterns (i.e., dry winter to wet summer). For example, in Arizona, summer monsoonal conditions often bring spectacular thunderstorms and flash floods to the Tucson area. The Asian monsoon brings several months of summer rain to India, Pakistan, and China. Some locations in India on the slopes of the Himalayas have annual rainfall as great as 25 m (83 ft), mostly in the 4-month summer period. In July and August 2010, the greatest monsoon rains in decades caused catastrophic flooding in Pakistan. During summer months, low-pressure, moisture-laden air moves north from the Indian Ocean and Arabian Sea. In the summer months of July and August 2010, strong monsoon storms moved through Pakistan. Annual rainfall in Pakistan is 25–50 cm (10–20 in) (mostly in July and August). On July 29, more than 30 cm (12 in) of rain fell on the headwaters of the Indus River that flows south through Pakistan to the sea. The result was catastrophic flooding.

The 2010 Pakistan floods killed about 1,600 people, and 20 million people were affected. Entire villages were washed away, and thousands of homes were flooded. Floodwaters covered about 557,000 ha (1.4 million acres) of agriculture land, and about 10,000 cows were killed.[2] The intense monsoon rains were a natural event, but some people have speculated that human processes played a role in the devastation. The population of Pakistan has grown greatly; in 1951, it was about 34 million, and in 2010, it was 170 million. Pakistan is the sixth most populous country on Earth. As Pakistan's population grew, more of the country's flood plains with forest and wetlands were converted to agricultural productivity. Urban areas grew,

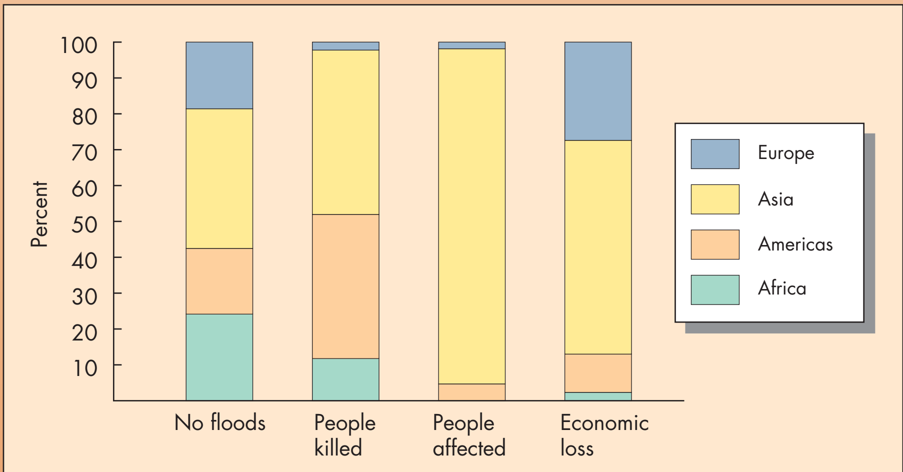


FIGURE 9.1 Global view of the flood hazard Notice that Asia is greatly affected by flooding. Based on data from 1997 to 2006. *(Center for Research on Epidemiology of Disasters (CRED) University of Louvain, Brussels, Belgium)*

(a)

(b)

FIGURE 9.2 Pakistan flood, 2010 (a) Map showing some of the areas of flooding. (b) Flooding of homes on floodplain of the Indus River. *(Kevin Frayer/AP Photo)*

and natural drainage was modified and clogged with sediment. A map of Pakistan with some of the areas that flooded in 2010 is shown on Figure 9.2a. Notice that the country is drained from the mountains to the north to the Arabian Sea by the Indus River. Most people in Pakistan live close to the river, and the huge increase in population in recent decades has placed millions of people at risk.

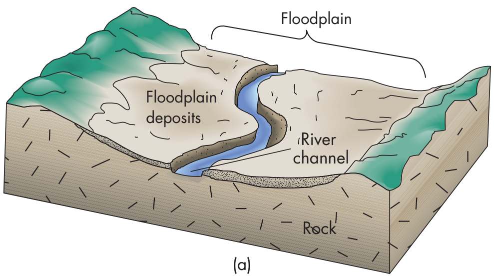
The most damaging floods in terms of lives lost in 2010 occurred in the northern part of the river basin, close to the high mountains. However, flood waters moved down-river, flooding the length of the country (Figure 9.2b). The damage to Pakistan from the floods was unprecedented, as about 6 million people were forced from their homes, sanitation conditions deteriorated, and people suffered greatly.

What does the Pakistan flooding of 2010 have to do with the flood hazard in the United States? We are a larger, much more wealthy country than Pakistan, with lower population growth, but we also have a significant flood hazard. For example, in early spring 2009, the Red River in North Dakota and Minnesota flooded once again, with record high flow. People worked around the clock to reinforce flood defenses, which included high walls consisting of millions of sandbags. Thousands of floodplain residences were evacuated from Fargo, North Dakota, and across the river at Moorhead, Minnesota. Several hundred large sandbags holding a ton of sand were dropped from helicopters in places where dikes were failing. All this reactive work helped during the flood, but, clearly, we need to rethink our philosophy of how we adjust to the flood hazard in the United States. As population continues to grow, we need to reduce the flood hazard in ways that do not require massive response but are proactive. We need plans for future flood hazard reduction that do not require massive evacuation from flood-prone areas but that avoid the hazard through land use. That is a proactive solution for future flooding in Pakistan as well.

Although flooding may be caused by several processes, including coastal flooding from a hurricane, in this chapter we will focus on river flooding. We will discuss flooding from several perspectives, including river processes, effects of land-use changes on flooding, effects of flooding, and how flooding may be minimized.

9.1 Rivers: Historical Use

For more than 200 years, Americans have lived and worked on floodplains, enticed to do so by the rich *alluvial* (i.e., stream-deposited) soil, abundant water supply, ease of waste disposal, and proximity to the commerce that has developed along the rivers. Of course, building houses, industry, public buildings, and farms on a floodplain invites disaster, but too many floodplain residents have refused to recognize the natural floodway of the river for what it is: part of the natural river system. The **floodplain**, the flat surface adjacent to the river channel that is periodically inundated by floodwater, is, in fact, produced by the process of flooding (**Figures 9.3a** and **9.4**). If the floodplain and its relationship to the river are not recognized, flood control and drainage of wetlands, including floodplains, become prime concerns. It is not an oversimplification to say that as the pioneers moved west, they had a rather set procedure for modifying the land: First, clear the land by cutting and burning the trees and then modify the natural drainage. Two parallel trends developed from that historical precedent: an accelerating program to control floods, matched by an even greater growth of flood damages. In this chapter, we will consider flooding as a natural aspect of river processes and examine the successes and failures of traditional methods of flood control. We will also discuss river restoration attempts that work with the natural river processes rather than against them.



(a)

(b)

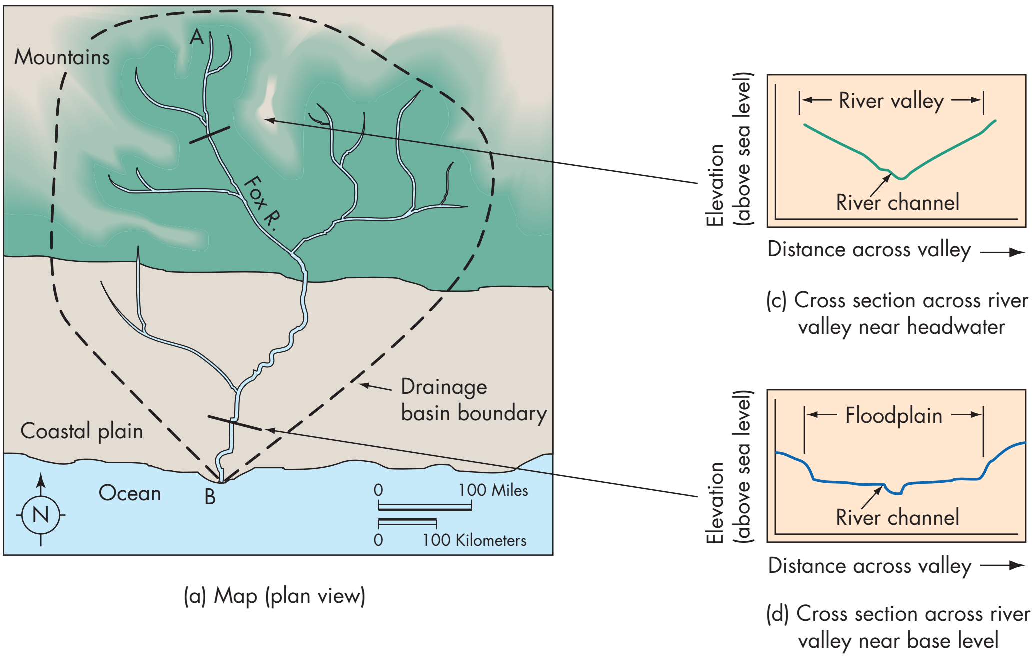
FIGURE 9.3 Floodplain (a) Diagram illustrating the location of a river's floodplain. (b) Floodplain of the Rio Grande in Colorado. *(Edward A. Keller)*

9.2 Streams and Rivers

Streams and rivers are part of the water, or hydrologic, cycle, and *hydrology* is the study of this cycle. The hydrologic cycle involves the transport of water by evaporation from Earth's surface, primarily from the oceans, to the atmosphere and, via surface and subsurface runoff from the land, back again to the oceans. Some of the water that falls on the land as rain or snow infiltrates soils and rocks; some evaporates; and the rest drains, or runs off, following a course determined by the local topography. This **runoff** finds its way to streams, which may merge to form a larger stream or a **river**. Streams and rivers differ only in size; that is, streams are small rivers. However, geologists commonly use the term *stream* for any body of water that flows in a channel.

Based on the geology, there are two basic types of rivers: the more common alluvial rivers where bed and banks of the river are sediment such as gravel and sand, or the less common bedrock rivers where bedrock is commonly exposed in the bed and banks. Bedrock streams and rivers are usually, but not always by any means, found in steep mountain areas. For example, sections of bedrock rivers (such as the Great Falls of the Potomac River) are located in the eastern United States at the boundary between the Piedmont (hard rocks) and Coastal Plane (soft rocks and sediment) known as the Fall Line, because rivers have a steeper gradient there, and there are bedrock rapids and water falls. Cities such as Troy, New York, Trenton, New Jersey, Washington D.C., Richmond Virginia, Raleigh, North Carolina, Columbia, South Carolina, and Augusta Georgia were sited on the Fall Line. It was difficult to move goods further upriver by boat past falls and rapids, but cities are not always sited at a barrier. More importantly, the steep gradients of the larger Fall Line rivers provided water power in the nineteenth century (prior to coal use) for emerging manufacturing industries. The region drained by a single river or river system is called a **drainage basin**, or *watershed* (**Figure 9.5a**).

FIGURE 9.4 Floodplain inundation from snowmelt Gaylor Creek, Yosemite National Park, during spring snowmelt. (a) In the morning, water is within the channel. (b) In the afternoon, during daily peak snowmelt, flow covers the floodplain. *(Edward A. Keller)*



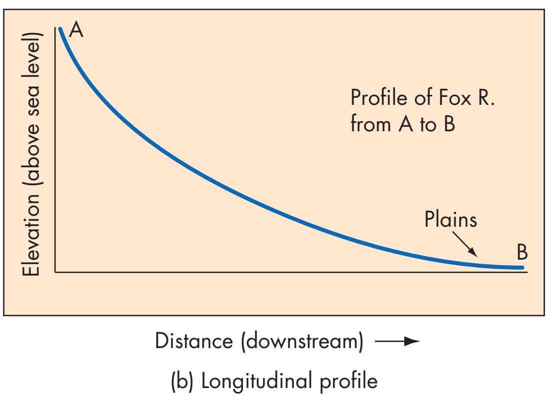


FIGURE 9.5 Drainage basin and river profile Idealized diagram showing (a) drainage basin, (b) longitudinal profile of the Fox River, (c) cross section of valley near headwater, and (d) cross section near base level.

A river's *slope*, or gradient, is the vertical drop of the channel over some horizontal distance. In general, the slope is steepest at higher elevations in the drainage basin and levels off as the stream approaches its *base level*. The base level of a stream is the theoretical lowest level to which a river may erode. Most often, the base level is at sea level, although a river may have a temporary base level such as a lake. Rivers flow downhill to their base level, and a graph of elevation of a river against distance downstream is called the longitudinal profile (Figure 9.5b). A river usually has a steeper-sided and deeper valley at high elevations near its headwaters than closer to its base level, where a wide floodplain may be present (Figure 9.5c, d). At higher elevations, the steeper slope of the river causes deeper erosion of the valley. Increased erosion is due to the higher flow velocity of the river water produced by the steeper channel slopes.

9.3 Sediment in Rivers

The total quantity of sediment carried in a river, called its *total load*, includes the bed load, the suspended load, and the dissolved load. The *bed load* moves by the bouncing, rolling, or skipping of particles along the bottom of the channel. The bed load of most rivers, usually composed of sand and gravel, is a relatively small component, generally accounting for less than 10 percent of the total load. The *suspended load*, composed mainly of silt and clay, is carried above the streambed by the flowing water. The suspended load accounts for nearly 90 percent of the total load and makes rivers look muddy. The *dissolved load* is carried in chemical solution and is derived from chemical weathering of minerals in rock, sediment and soil in the drainage basin. The dissolved load may make stream water taste salty if it contains large amounts of sodium and chloride. It may also make the stream water "hard" if the dissolved load contains high concentrations of calcium and magnesium. The most common constituents of the dissolved load are bicarbonate ions (HCO_3^-), sulfate ions (SO_4^{2-}), calcium ions(Ca^{2+}), sodium ions (Na^+), and magnesium ions (Mg^+). As discussed in Chapter 3, an ion is an atom or a molecule with a positive or negative charge resulting from a gain or loss of electrons. Typically, the five previously mentioned ions constitute more than 90 percent of a river's dissolved load. It is the suspended and bed loads of streams that, when deposited in undesirable locations, produce the sediment pollution discussed in Chapter 14.

9.4 River Velocity, Discharge, Erosion, and Sediment Deposition

Rivers are the basic transportation system of the part of the rock cycle that involves erosion and deposition of sediments. They are a primary erosion agent in the sculpting of our landscape. The velocity, or speed, of the water in a river varies along its course, affecting both erosion and deposition of sediment.

Discharge (Q) is the volume of water moving by a particular location in a river per unit time. It is reported in cubic meters per second (cms) or cubic feet per second (cfs). Discharge is calculated as

$$Q = W \times D \times V$$

where Q is discharge (cubic meters per second), W is the width of flow in meters, D is depth of flow in meters, and V is mean velocity of flow (meters per second). The equation $Q = W \times D \times V$ is known as the **continuity equation** and is one of the most important relationships in understanding the flow of water in rivers. We assume that if there are no additions or deletions of flow along a given length of river, then discharge is constant. It follows that if the cross-sectional area of flow ($W \times D$) decreases, the velocity of the water must increase. You can observe this change with a garden hose. Turn on the water and observe the velocity of the water as it exits the hose. Then put your thumb partly over the end of the hose, reducing the area where the water flows out of the hose, and observe the increase in the velocity. This concept explains why a narrow river channel in a canyon has a higher velocity of flow. It is also the reason that rapids are common in narrow canyons. In general, a faster-flowing river has the ability to erode its banks more than a slower-moving one. Streams that flow from mountains onto plains may form fan-shaped deposits known as *alluvial fans* (**Figure 9.6**). Rivers flowing into the ocean or some other body of still water may deposit sediments that form a *delta*, a triangular or irregular-shaped landmass extending into the sea or a lake (**Figure 9.7**). The flood hazard associated with alluvial fans and deltas is different from hazards in a river valley and floodplain environment because rivers entering

FIGURE 9.6 Alluvial fan Alluvial fan along the western foot of the Black Mountains, Death Valley. Note the road along the base of the fan. The white materials are salt deposits in Death Valley. *(Michael Collier)*

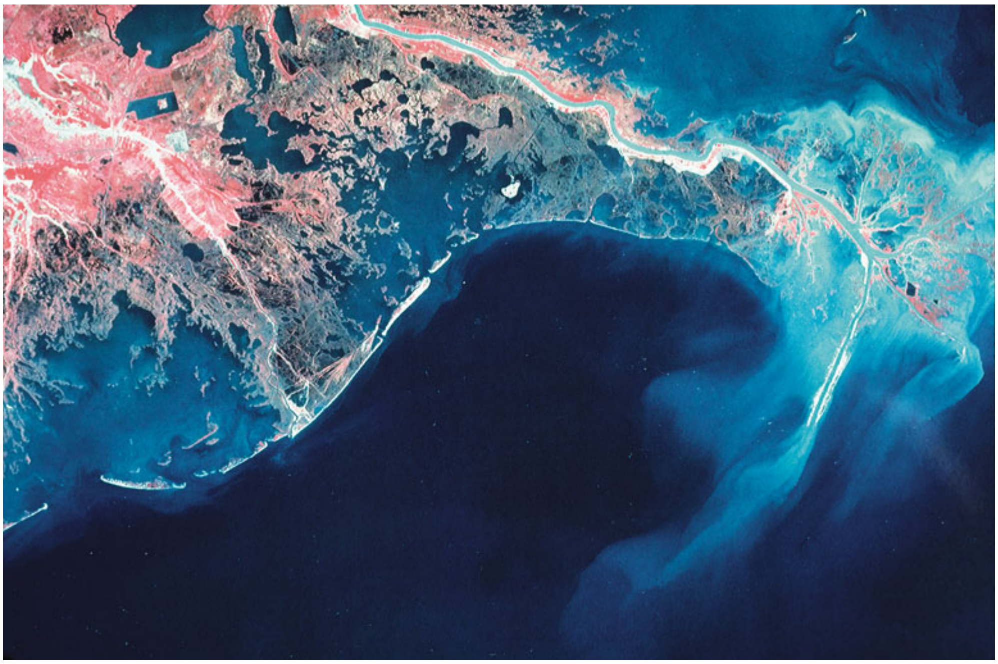


FIGURE 9.7 Delta The delta of the Mississippi River. In this false-color image, vegetation appears red, and sediment-laden waters are white or light blue; deeper water with less suspended sediment is a darker blue. The system of distributary channels of the river in the delta in the far right of the photograph looks something like a bird's foot, and, in fact, the Mississippi River delta is an example of a bird's-foot delta. The distributary channels carry sediment out into the Gulf of Mexico, and, because wave action is not strong in the gulf, the river dominates the delta system. Distance across the image is about 180 km (112 mi). Other rivers flow into a more active coastal environment. Such deltas have a relatively straight coastline, rather than bird's-foot shape, and are considered to be wave dominated. Other deltas are between the end points of river domination and wave domination, as, for example, the Nile delta with its beautiful triangular shape and its convex shoreline protruding into the Mediterranean Sea. *(University of Washington Libraries)*

alluvial fan or delta environments often split into a system of *distributary channels*. That is, the river no longer has only one main channel but has several channels that carry floodwaters to different parts of the fan or delta. Furthermore, these channels characteristically may change position rapidly during floods, producing a flood hazard that is difficult to predict.[3] For example, a large recreational vehicle (RV) park on the delta of the Ventura River in southern California flooded four times in the 1990s. The RV park was constructed across a historically active distributary channel of the Ventura River. However, before the construction of the park, the engineers mapping the potential flood hazards on the site did not recognize that the park was located on a delta. This story emphasizes the importance of studying a river's flooding history as part of flood hazard evaluation (see A Closer Look: History of a River).

The reasons erosion or deposition occurs in a specific area of river channel or on alluvial fans or deltas are complex, but they can be correlated to the physical properties of the river:

- Change in channel width, depth, or slope
- Composition of channel bed and banks (rock, gravel, sand, silt, or clay)
- Type and amount of vegetation
- Land use, such as clearing a forest for agriculture (discussed in Section 9.5)

For example, deposition on alluvial fans occurs in part because of changes in the shape and slope of distributary channels. They often become wider and shallower with a decreasing slope, and this change decreases the velocity of flow, favoring deposition. In general, as the velocity of flow in a river increases, the size of the bed load it can transport increases, as does the volume of suspended load consisting of silt and clay-sized particles. Specific relationships between flow velocity, discharge, and sediment transport are beyond the scope of our discussion here.

The largest particle (diameter in millimeters or centimeters) a river may transport is called its *competency*. The total load, by mass or weight, of sediment that a river carries in a given period of time is called its *capacity*.

9.5 Effects of Land Use Changes

Streams and rivers are open systems that generally maintain a rough *dynamic equilibrium*, or steady state between the work done (i.e., the sediment transported by the stream) and the load imposed (i.e., the sediment delivered to the stream from tributaries and hill slopes). A stream tends to have a slope and cross-sectional shape that provides the velocity of flow necessary to do the work of moving the sediment load.[6] An increase or a decrease in the amount of water or sediment received by the stream usually brings about changes in the channel's slope or cross-sectional shape, effectively changing the velocity of the water. The change of velocity may, in turn, increase or decrease the amount of sediment carried in the system. Therefore, land-use changes that affect the stream's volume of sediment or water volume may set into motion a series of events that results in a new dynamic equilibrium.

Consider, for example, a land use change from forest to agricultural row crops. This change will cause increased soil erosion and an increase in the sediment load supplied to the stream because agricultural lands have higher soil erosion rates than forested lands. At first, the stream will be unable to transport the entire load and will deposit more sediment, increasing the slope of the channel. The steeper slope of the channel will increase the velocity of water and allow the stream to move more sediment. If the base level is fixed, the slope will continue to increase by deposition in the channel until the increase in velocity is sufficient to carry the new load. If the notion that deposition of sediment increases channel slope is counterintuitive to you, see **Figure 9.8** for an illustration of this principle. A new dynamic equilibrium may be reached, provided that the rate of sediment increase levels out

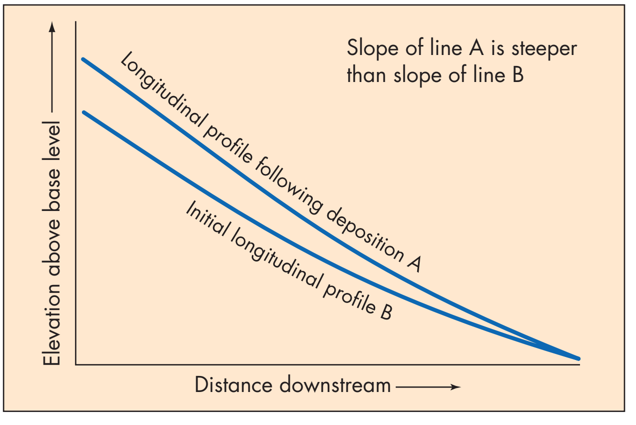


FIGURE 9.8 Effect of deposition on river slope
Idealized diagram illustrating that deposition in a stream channel results in an increase in channel gradient.

A Closer Look

History of a River

In 1905, philosopher George Santayana said, "Those who cannot remember the past are condemned to repeat it." Scholars may debate the age-old question of whether cycles in human history repeat themselves, but the repetitive nature of natural hazards, such as floods, is undisputed.[4] Better understanding of the historical behavior of a river is, therefore, valuable in estimating its present and future flood hazards. Consider the February 1992 Ventura River flood in southern California. The flood severely damaged the Ventura Beach Recreational Vehicle (RV) Resort, which had been constructed a few years earlier on an active distributary channel of the Ventura River delta. Although the recurrence interval is approximately 22 years (**Figure 9.A**), earlier engineering studies suggested that the RV park would not be inundated by a flood with a recurrence interval of 100 years. What went wrong?

- Planners did not recognize that the RV park was constructed on a historically active distributary channel of the Ventura River delta. In fact, early reports did not even mention a delta.
- Engineering models that predict flood inundation are inaccurate when evaluating distributary channels on river deltas where extensive channel fill and scour as well as lateral movement of the channel are likely to occur.
- Historical documents, such as maps dating back to 1855 and more-recent aerial photographs that showed the channels, were not evaluated. **Figure 9.B** shows that maps rendered from these documents suggest that the distributary channel was in fact present in 1855.[5]

Clearly, the historical behavior of the river was not evaluated as part of the flood-hazard evaluation. If it had been, the site would have been declared unacceptable for development, given that a historically active channel was present. Nevertheless, necessary permits were issued for development of the park, and, in fact, the park was rebuilt after the flood. Before 1992, the distributary channel carried discharges during 1969, 1978, and 1982. After the 1992 flood event, the channel carried floodwaters in the winters of 1993, 1995, and 1998, again flooding the RV park. During the 1992 floods, the discharge increased from less than 25 m^3 per second (883 ft^3 per second) to a peak of

FIGURE 9.A Flooding of California's Ventura Beach RV Resort in February 1992 The RV park was built directly across a historically active distributary channel of the Ventura River delta. The recurrence interval of this flood is approximately 22 years. A similar flood occurred again in 1995. Notice that U.S. Highway 101 along the Pacific Coast is completely closed by the flood event. *(Mark J. Terrell/AP Photo)*

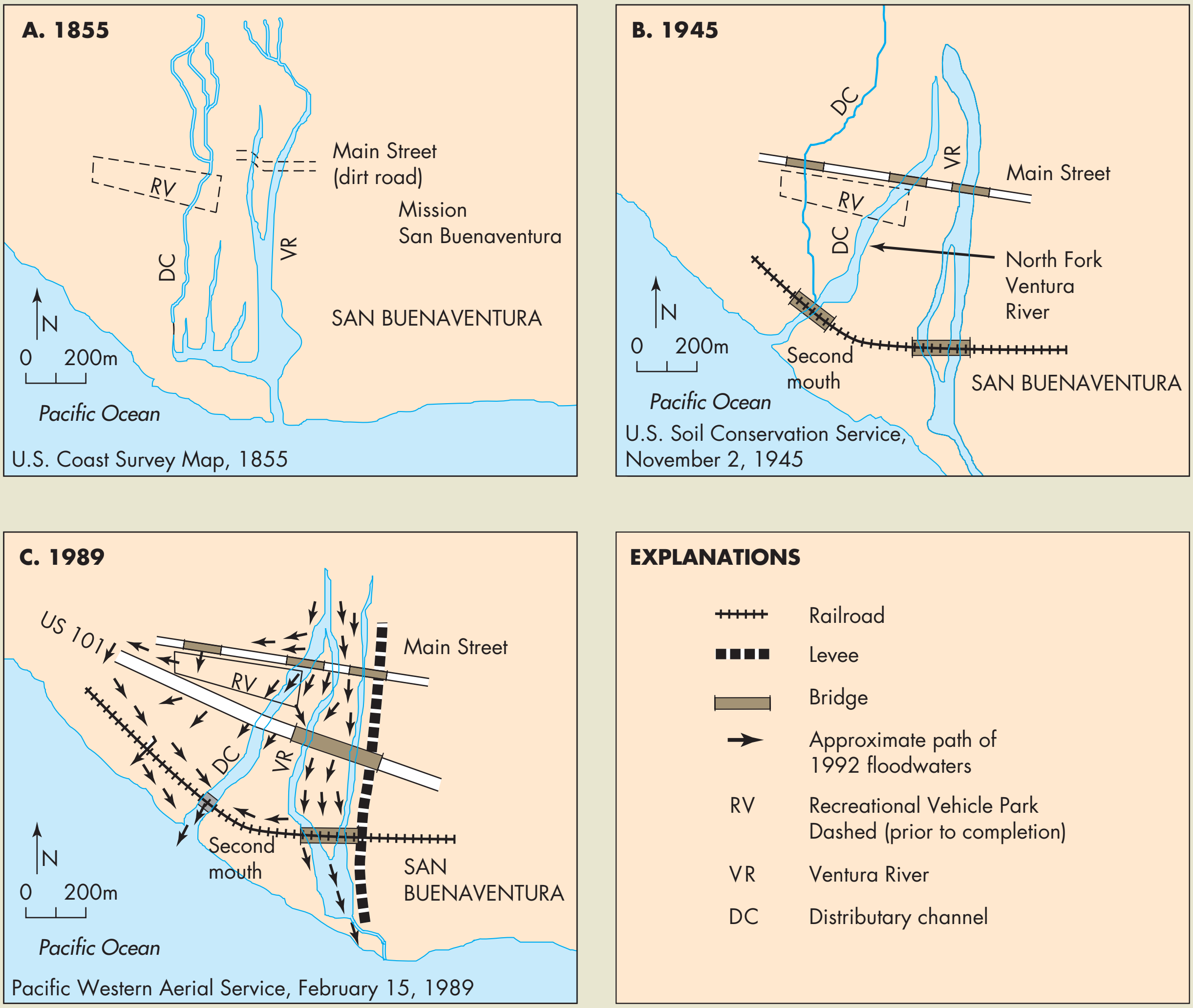


FIGURE 9.B Historical maps of the Ventura River delta The maps show the distributary channel and the location of the RV park. *(From Keller, E. A., and Capelli, M. H. 1992. Ventura River flood of February, 1992: A lesson ignored?* Water Resources Bulletin *28(5):813–831)*

1,322 m^3 per second (46,683 ft^3 per second) in only about 4 hours! This is approximately twice as much as the daily high discharge of the Colorado River through the Grand Canyon in the summer, when it is navigated by river rafters. This is an incredible discharge for a relatively small river with a drainage area of only about 585 km^2 (226 mi^2). The flood occurred during daylight, and one person was killed. If the flood had occurred at night, many more deaths would have been recorded. A warning system that has been developed for the park has, so far, been effective in providing early warning of an impending flood. The park, with or without the RVs and people, is a "sitting duck." Its vulnerability was dramatically illustrated in 1995 and 1998, when winter floods again swept through the park. Although the warning system worked and the park was successfully evacuated, the facility was again severely damaged. Following the 1992 flood, there was a movement to purchase the park and restore the land to a more natural delta environment; a good move that by 2011 has not materialized and the RV park remains a sitting duck for the next big flood.

and the channel slope and shape can adjust before another land-use change occurs. Suppose the reverse situation now occurs—that is, farmland is converted to forest. The sediment load to the stream from the land will decrease, and less sediment will be deposited in the stream channel. Erosion of the channel will eventually lower the slope; the lowering of the slope will, in turn, lower the velocity of the water. The predominance of erosion over deposition will continue until equilibrium between the total load imposed and work done is achieved again.

The sequence of change just described occurred in parts of the southeastern United States. On the Piedmont, between the Appalachian Mountains and the coastal plain, forestland had been cleared for farming by the 1800s. The land use change from forest to farming accelerated soil erosion and subsequent deposition of sediment in the stream (**Figure 9.9**). This acceleration caused the preagriculture channel to fill with sediment, as shown in Figure 9.9. After 1930, the land reverted to pine forests, and this reforestation, in conjunction with soil conservation measures, reduced the sediment load delivered to streams. Thus, formerly muddy streams choked with sediment had cleared and eroded their channels by 1969.

Consider now the effect of constructing a dam on a stream. Considerable changes will take place both upstream and downstream of the reservoir created behind the dam. Upstream, at the head of the reservoir, the water in the stream will slow down, causing deposition of sediment. Downstream, the water coming out below the dam will have little sediment, since most of it has been trapped in the reservoir. As a result, the stream may have the capacity to transport additional sediment; if this happens, channel erosion will predominate over deposition downstream of the dam. The slope of the stream will then decrease until new equilibrium conditions are reached (**Figure 9.10**). (We will return to the topic of dams on rivers in Chapter 13.)

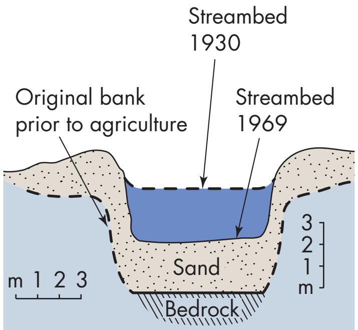


FIGURE 9.9 Streambed changes from land use changes Accelerated sedimentation and subsequent erosion resulting from land-use changes (natural forest to agriculture and back to forest) at the Mauldin Millsite on the Piedmont of middle Georgia. *(After Trimble, S. W. 1969. "Culturally accelerated sedimentation on the middle Georgia Piedmont." Master's thesis, Athens: University of Georgia. Reproduced by permission)*

9.6 Channel Patterns and Floodplain Formation

The configuration of the channel as seen in an aerial view is called the **channel pattern**. Channel patterns can be braided or meandering, or both characteristics may be found in the same river. *Braided* channels (**Figure 9.11**) are characterized by numerous gravel bars and islands that divide and reunite the channel. A steep slope and coarse sediment favor transport of bed load material important in the development of gravel bars that form the "islands" that divide and subdivide the flow. The formation of the braided channel pattern, as with many other river forms, results from the interaction

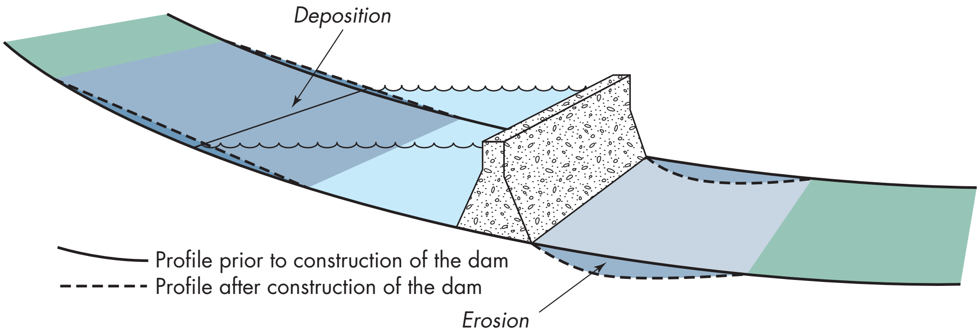


FIGURE 9.10 Effect of a dam on erosion Upstream deposition and downstream erosion from construction of a dam and a reservoir.

(a)

(b)

FIGURE 9.11 Braided channels (a) The north Saskatchewan River, shown here, has a braided channel pattern. Notice the numerous channel bars and islands that subdivide the flow. *(University of Washington Libraries)* (b) Ground view of a braided channel in Granada in southern Spain with multiple channels, a steep gradient, and coarse gravel. The distance across the channel is about 7 m (21 ft). *(Edward A. Keller)*

of flowing water and moving sediment. If the river's longitudinal profile is steep and there is an abundance of coarse bed load sediment, the channel pattern is likely to be braided. Braided channels tend to be wide and shallow compared with meandering rivers. They are often associated with steep rivers flowing through areas that are being rapidly uplifted by tectonic processes. They are also common in rivers receiving water from melting glaciers that provide a lot of coarse sediment.

Some channels contain *meanders*, which are bends that migrate back and forth across the floodplain (**Figure 9.12a**). Although we know what meander bends look like and what the water and sediment do in the bends, we do not know for sure why rivers meander. On the outside of a bend, sometimes referred to as the *cut bank*, the water moves faster during high flow events, causing more bank erosion; on the inside of a curve, water moves more slowly, and sediment is deposited, forming *point bars*. As this differential erosion and sediment deposition continues, meanders migrate laterally by erosion on the cut banks and by deposition on point bars, a process that is prominent in constructing and maintaining some floodplains (Figure 9.12b). Overbank deposition, or deposition beyond the banks of a river, during floods causes layers of relatively fine sediments, such as sand and silt, to build upward; this accumulation is also important in the development of floodplains. Much of the sediment transported in rivers is periodically stored by deposition in the channel and on the adjacent floodplain. These areas, collectively called the *riverine environment*, are the natural domain of the river.

Meandering channels often contain a series of regularly spaced pools and riffles (**Figure 9.13**, page 302). *Pools* are deep areas produced by scour, or erosion at high flow, and characterized at low flow by relatively deep, slow movement of water. Pools are places in which you might want to take a summer swim. *Riffles* are shallow areas produced by depositional processes at high flow and characterized by relatively shallow, fast-moving water at low flow. Pools and riffles have important environmental significance: The alternation of deep, slow-moving water with shallow, fast-moving water in pools and riffles produces a variable physical and hydrologic environment and increased biological diversity.[7] For example, fish may feed in riffles and seek shelter in pools, and pools have different types of insects than are found in riffles.

Having presented some of the characteristics and processes of flow of water and sediment in rivers, we will now discuss the process of flooding in greater detail.

9.7 River Flooding

The natural process of *overbank flow* is termed **flooding** (see Figure 9.4). Most river flooding is a function of the total amount and distribution of precipitation in the drainage basin, the rate at

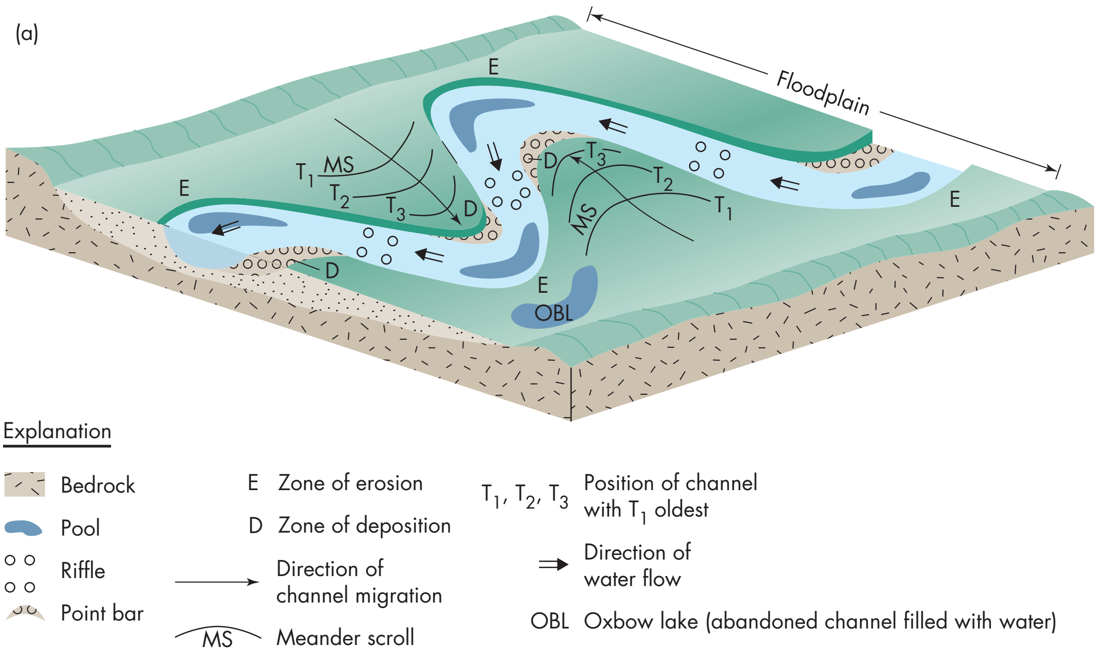


FIGURE 9.12 Meandering river (a) Idealized diagram of a meandering stream and important forms and processes. Meander scrolls are low, curved ridges of sediment parallel to a meander bend. They form at the edge of a riverbank as sediment accumulates with plants. A series of scrolls marks the evolution of a meander bend. (b) Koyakuk River, Alaska, showing meander bend, point bar, and cut bank. The Oxbow lake formed as the river eroded laterally across the floodplain and "cut off" a meander bend, leaving the meander bend as a lake. *(Accent Alaska/Alamy)*

which precipitation infiltrates the rock or soil, and the topography. Some floods, however, result from rapid melting of ice and snow in the spring or, on rare occasions, from the failure of a dam. Finally, land use can greatly affect flooding in small drainage basins.

The channel discharge at the point where water overflows the channel is called the *flood discharge* and is used as an indication of the magnitude of the flood (see A Closer Look: Magnitude and Frequency of Floods). The height of the water in a river at any given time is called the *stage*. The term *flood stage* frequently connotes that the water surface has reached a high-water condition likely to cause damage to personal property. This definition is based on human perception of the event, so the elevation that is considered flood stage depends on human use of the floodplain.[8] Therefore, the magnitude of a flood may or may not coincide with the extent of property damage.

Flash Floods and Downstream Floods

It is useful to distinguish between flash and downstream floods (Figure 9.14, page 302). **Flash floods** occur in the upper parts of drainage basins and are

A Closer Look

Magnitude and Frequency of Floods

Flooding is intimately related to the amount and intensity of precipitation and runoff. Catastrophic floods reported on television and in newspapers are often produced by infrequent, large, intense storms. Smaller floods or flows may be produced by less intense storms that occur more frequently. All flow events that can be measured or estimated from a stream-gauging station (**Figure 9.C**) can be arranged in order of their magnitude of discharge, generally measured in cubic meters per second (**Figure 9.D**). The list of annual peak flows—that is, the largest flow each year or the annual series so arranged (see data for the Patrick River in the table adjacent to **Figure 9.E**)—can be plotted on a discharge-frequency curve by deriving the recurrence interval (R) for each flow from the relationship

$$R = (N + 1)/M$$

where R is a recurrence interval in years, N is the number of years of record, and M is the rank of the individual flow within the recorded years (Figure 9.E).[9] For example, in Figure 9.E, the highest flow for 9 years of data for the stream is approximately 280 m^3 per second (9,888 ft^3 per second) and has a rank M equal to 1.[10] The recurrence interval of this flood is

$$R = \frac{N + 1}{M} = \frac{9 + 1}{1} = 10$$

which means that a flood with a magnitude equal to or exceeding 280 m^3 per second can be expected about every 10 years; we call this a 10-year flood. The probability that the 10-year flood will happen in any one year is 1/10, or 0.1 (10 percent). The probability that the 100-year flood will occur in any one year is 1/100, or 0.01 (1 percent). The curve in Figure 9.E is extended by extrapolation to estimate the discharge of the 20-year flood at 450 cms. Extrapolation is risky and shouldn't extend much beyond two times the length of recorded values of discharge. Studies of many streams and rivers show that channels are formed and maintained by bankfull discharge, defined as a flow with a recurrence interval of about 1.5 years (27 m^3 per second in Figure 9.E). Bankfull is the flow that just fills the channel. Therefore, we can expect a stream to emerge from its banks and cover part of the floodplain with water and sediment once every year or so.

As flow records are collected, we can more accurately predict floods. However, designing structures for a 10-year, 25-year, 50-year, or even 100-year flood, or, in fact, any flow, is a calculated risk since predicting such floods is based on a statistical probability. In the long term, a 25-year flood happens on the average of once every 25 years, but two 25-year floods could occur in any given year, as could two 100-year floods![11] As long as we continue to build dams, highways, bridges, homes, and other structures without considering the effects on flood-prone areas, we can expect continued loss of lives and property.

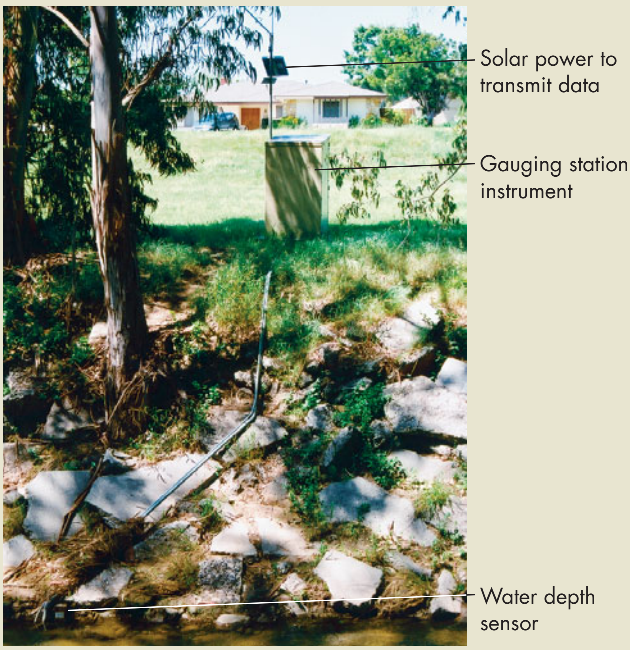


FIGURE 9.C Stream-gauging station San Jose Creek, Goleta, California. *(Edward A. Keller)*

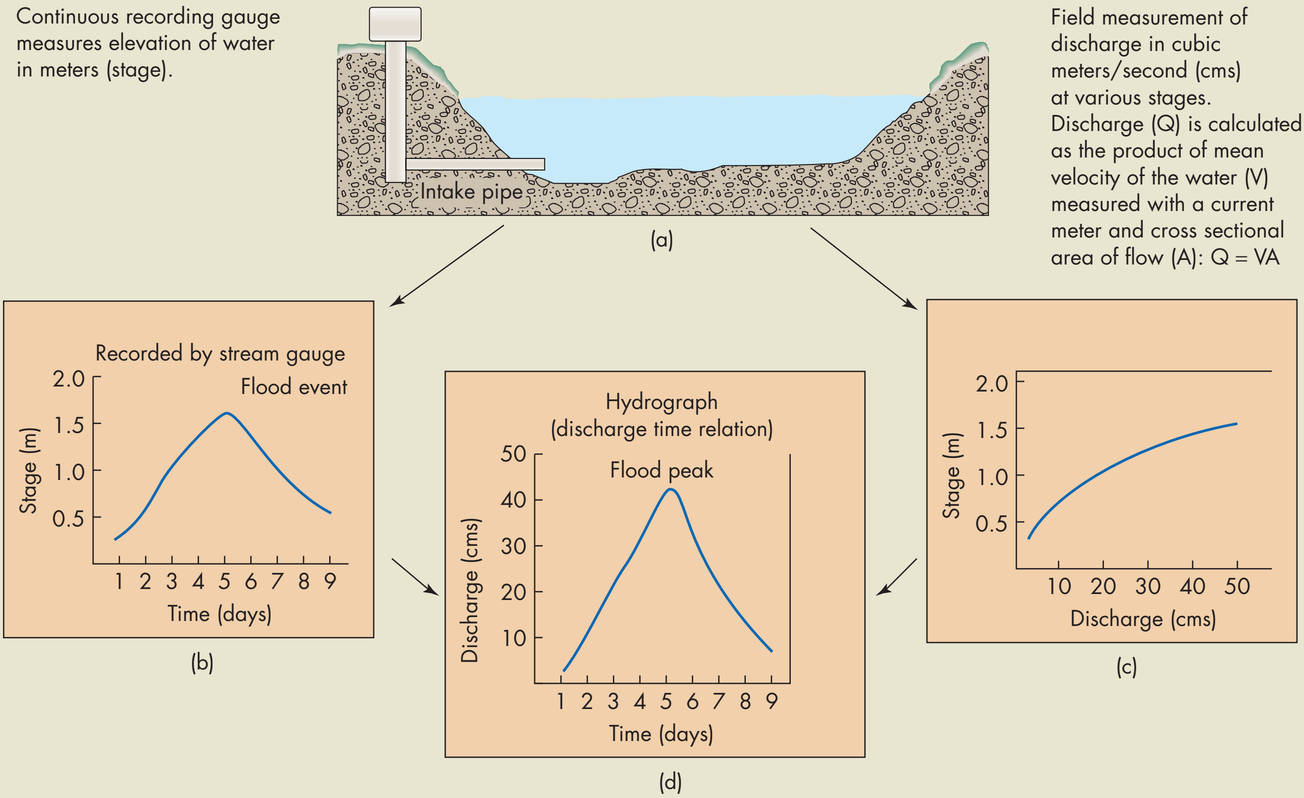


FIGURE 9.D How a hydrograph is produced Field data (a) consist of a continuous recording of the water level, or stage, which is used to produce a stage-time graph (b). Field measurements at various flows also produce a stage-discharge graph (c). Graphs (b) and (c) are combined to produce the final hydrograph (d).

Patrick River
Stream Gauge Data
Peak Annual Flow

Year	Discharge (cms)	M	R (yrs)
1995	30	5	2.0
1996	280	1	10.0
1997	45	4	2.5
1998	28	6	1.7
1999	120	2	5.0
2000	26	7	1.4
2001	100	3	3.3
2002	23	8	1.3
2003	20	9	1.1

M = Magnitude where M = 1 is the highest flow on record

R = Recurrence Interval in years; calculated by $R = \frac{N+1}{M}$; for Patrick River N = 9

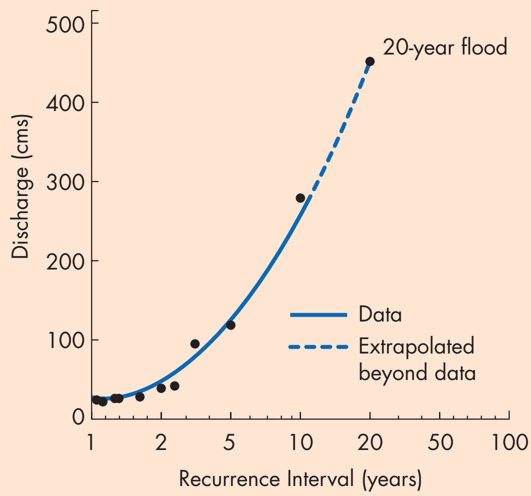


FIGURE 9.E Example of a discharge–frequency curve This curve is for the Patrick River on the adjacent table. The curve is extended (extrapolated) to estimate the 20-year flood at about 450 cms.

FIGURE 9.13 Pool and riffle Well-developed pool-riffle sequence in Sims Creek near Blowing Rock, North Carolina. A deep pool is apparent in the middle distance, and shallow riffles can be seen in the far distance and in the foreground. *(Edward A. Keller)*

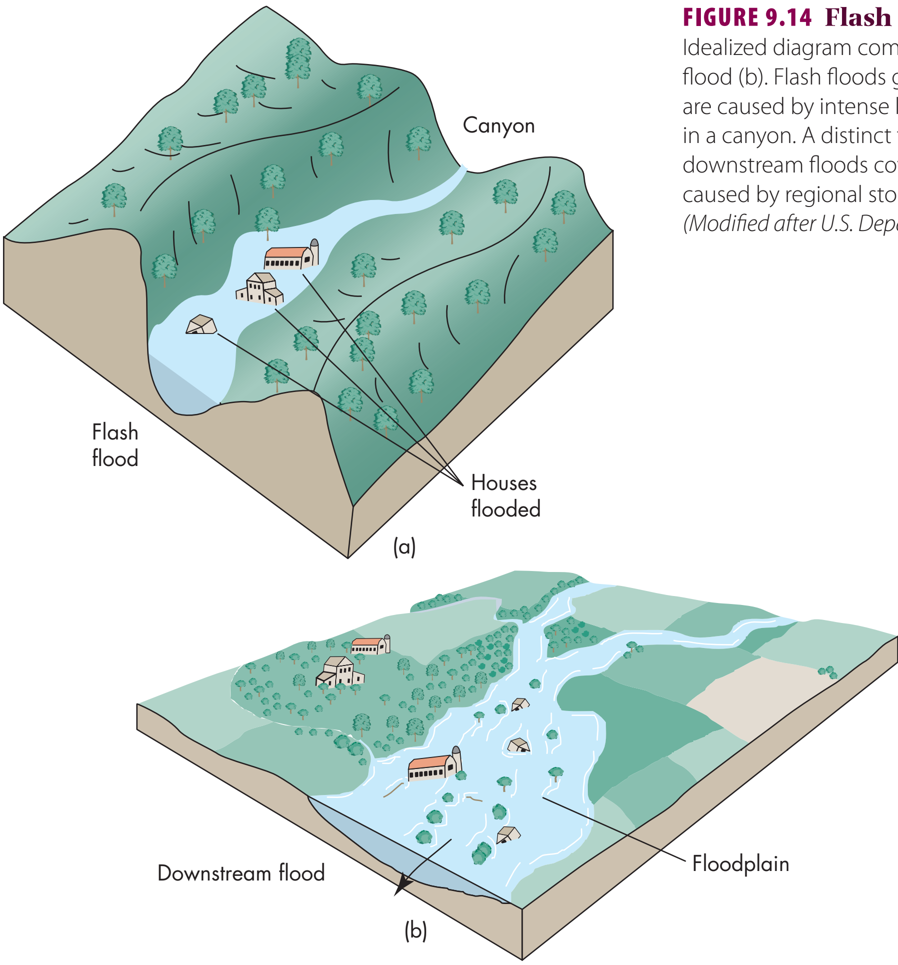


FIGURE 9.14 Flash floods and downstream floods Idealized diagram comparing a flash flood (a) with a downstream flood (b). Flash floods generally cover relatively small areas and are caused by intense local storms with steep topography, often in a canyon. A distinct floodplain may not be present, whereas downstream floods cover wide areas of a floodplain and are caused by regional storms or spring runoff of a floodplain. *(Modified after U.S. Department of Agriculture drawing)*

generally produced by intense rainfall of short duration over a relatively small area. In general, flash floods may not cause flooding in the larger streams they join downstream, although they can be quite severe locally. For example, a flash flood in June of 2010, fueled by intense rain, roared through a remote campground along the banks of the Little Missouri River in western Arkansas. The flood started about 2 A.M. when campers in tents and RVs were asleep. The small river rose rapidly and in a short time was several meters deep and moving fast (roaring)

FIGURE 9.15 Flash flood rescue Man being rescued after his vehicle was washed into a flooded river near Jackson, Missouri on March 18, 2008. *(Aaron Eisenhauer/ AP Photo)*

through the campground, washing tents, cars, RVs, and people down stream valley in the dark. The power of the flow tore up roads, peeling asphalt and debarking trees. The flood claimed 16 lives, hospitalizing 20 others, and 60 people were rescued.

A high-magnitude flash flood that occurred in July 1976 in the Front Range of Colorado was caused by violent flash floods, which are characterized by a rapid rise in floodwaters in response to precipitation. In addition, the flash floods were nourished by a complex system of thunderstorms that swept through several canyons west of Loveland, delivering up to 25 cm (9.8 in.) of rain. This brief local flood killed 139 people and caused more than $35 million in damages to highways, roads, bridges, homes, and small businesses. Most of the damage and loss of life occurred in the Big Thompson Canyon, where hundreds of residents, campers, and tourists were caught with little or no warning. Although the storm and flood were rare events in the Front Range canyons, comparable floods have occurred in the past and others can be expected in the future.[12–14] Interestingly, the U.S. Geological Survey reports that about half of all the U.S. deaths during flash floods are related to automobiles. When people attempt to drive through shallow, fast-moving floodwater, the strong lateral force of the water may sweep automobiles off the road into deeper water, trapping people in sinking or overturned vehicles (**Figure 9.15**).

It is the large **downstream floods**, such as the 1993 Mississippi River flood and the 1997 Red River, North Dakota, flood, that usually make television and newspaper headlines. Floodwaters of the Red River, which flows north to Canada, inundated the city of Grand Forks, North Dakota, initiating the evacuation of 50,000 people, causing a fire that burned part of the city center and more than $1 billion in damage (**Figure 9.16**). The Red River often floods in the spring, and it did so again in the spring of 2001, when heavy rains melted snow and ice on frozen ground that did not allow infiltration of the rain into the forest.

Downstream floods cover a wide area and are usually produced by storms of long duration that saturate the soil and produce increased runoff. Flooding on small tributary basins is limited, but the contribution of increased runoff from thousands of tributary basins may cause a large flood downstream. A flood of this kind is characterized by the downstream movement of the floodwaters with a large rise and fall of discharge at a particular location.[15] **Figure 9.17a** (page 305) shows an area map and Figure 9.17b shows the 257 km (160 mi) downstream migration of a flood crest on the Chattooga–Savannah River system. It illustrates that a progressively longer time is

FIGURE 9.16 Flooded city Flooding of the Red River at Grand Forks, North Dakota, in 1997 caused a fire that burned part of the city. *(Eric Hylden/Grand Forks Herald)*

necessary for the rise and fall of water as the flood wave proceeds downstream. In addition, it dramatically shows the tremendous increase in discharge from low-flow conditions to more than 1,700 m^3 per second (60,000 ft^3 per second) in 5 days.[16] Figure 9.17c illustrates the same flood in terms of discharge per unit area, eliminating the effect of downstream increase in discharge. This better illustrates the shape and form of the flood peak as it moves downstream.[16]

9.8 Urbanization and Flooding

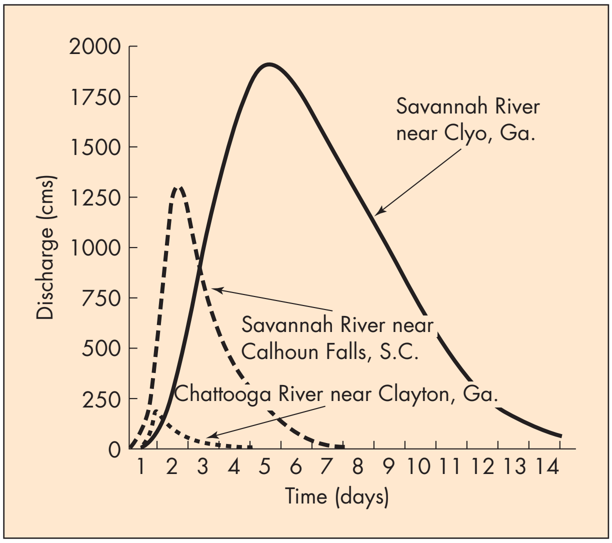
Human use of land in urban environments has increased both the magnitude and frequency of floods in small drainage basins of a few square kilometers. The rate of increase is a function of the percentage of the land that is covered with roofs, pavement, and cement, referred to as *impervious cover* (**Figure 9.18**), and the percentage of area served by storm sewers. Storm sewers are important because they allow urban runoff from impervious surfaces to reach stream channels much more quickly than in natural settings. Therefore, impervious cover and storm sewers are collectively a measure of the degree of urbanization. The graph in **Figure 9.19** (page 306) shows that an urban area with 40 percent impervious surface and 40 percent of its area served by storm sewers can expect to have about three times as many floods as before urbanization. This ratio applies to floods of small and intermediate frequency. As the size of the drainage basin increases, however, high-magnitude floods with frequencies of approximately 50 years are not significantly affected by urbanization (**Figure 9.20**, page 306).

Floods are a function of rainfall–runoff relationships, and urbanization causes a tremendous number of changes in these relationships. One study showed that urban runoff from large storms is nearly five times that of preurban runoff.[17] Estimates of discharge for different recurrence intervals at different degrees of urbanization are shown in **Figure 9.21** (page 306). The estimates clearly indicate the tremendous increase of runoff with increasing impervious areas and storm sewer coverage. However, it is not only the peak discharge that causes urban flooding. Long-duration storms resulting from moderate precipitation can also cause flooding if storm drains become blocked with sediment and storm debris. In this case, water begins to pond, causing flooding in low areas. It is analogous to water rising in a bathtub shower when the drain becomes partly blocked by soap.

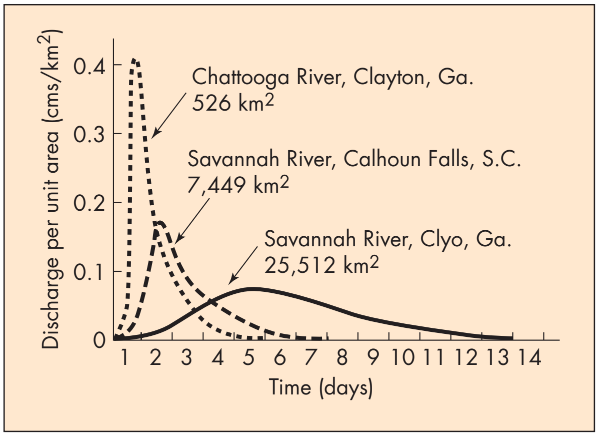
Urbanization causes increased runoff because less water infiltrates the ground. **Figure 9.22a** (page 307) shows a generalized hydrograph before urbanization. Of particular importance is the *lag time*, defined as the time between when most of the rainfall occurs and a flood is produced. Figure 9.22b shows two hydrographs, before and after urbanization. Note the significant reduction in lag time after urbanization. Short lag times, referred to as *flashy discharge*, are characterized by rapid rise and fall of floodwater. Since little water infiltrates the soil, the low water or dry-season flow in urban streams, normally sustained by groundwater seepage into the channel, is greatly reduced. This reduction in flow effectively concentrates any pollutants present and generally lowers the aesthetic amenities of the stream.[10]

(a)

FIGURE 9.17 Downstream movement of a flood wave Downstream movement of a flood waters on the Savannah River, South Carolina and Georgia. The distance from Clayton to Clyo is 257 km (160 mi). (a) Map of the area. (b) Volume of water passing Clayton, Calhoun Falls, and Clyo. (c) Volume of water per unit area at the same points. *(After Hoyt, W. G., and Langbein, W. B. Floods. © Copyright 1955 by Princeton University Press, figure 8, p. 39. Reprinted by permission of Princeton University Press)*



(b)



(c)

FIGURE 9.18 Urbanization increases runoff Cities in most of the United States, such as Santa Barbara, California, shown here, have a high portion of their land covered by roofs, streets, and parking lots. These surfaces do not allow water to infiltrate the ground, so surface runoff greatly increases. *(Edward A. Keller)*

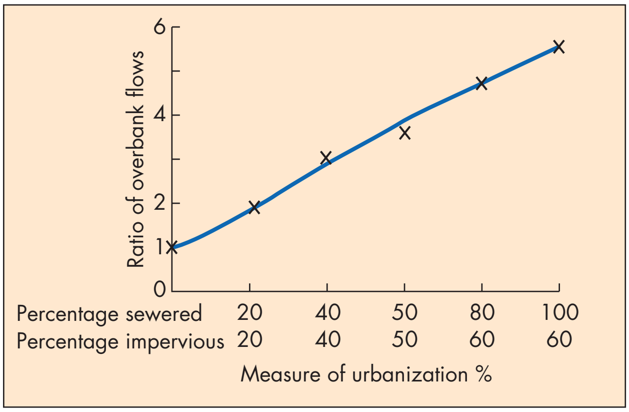


FIGURE 9.19 Floods before and after urbanization Relationship between the ratio of overbank flows (i.e., after urbanization to before urbanization) and measure of urbanization. This concept also refers to suburban and rural areas where in impervious cover has increased from land use such as parking lots and buildings in shopping malls. For example, a ratio of 3 to 1, or simply 3, means that, after urbanization, there are three floods for every one there was before urbanization; that is, flooding is three times as common after urbanization. This figure shows that as the degree of urbanization increases, the number of overbank flows per year also increases. *(After Leopold, L. B. 1968. U.S. Geological Survey Circular 559)*

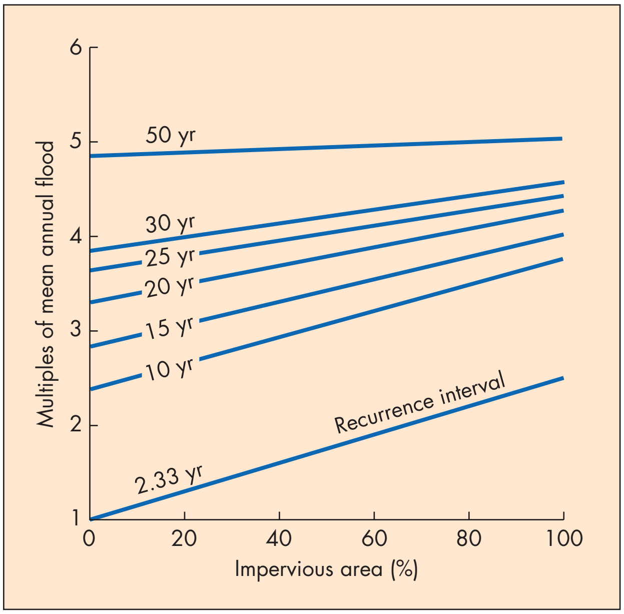


FIGURE 9.20 Urban flood hazard increases as impervious area increases Graph showing the variation of flood frequency with percentage of impervious area. The mean annual flood (approximately bankfull) is the average (over a period of years) of the largest flow that occurs each year. The mean annual flood in a natural river basin with no urbanization has a recurrence interval of 2.33 years. Note that the smaller floods with recurrence intervals of just a few years are much more affected by urbanization than are the larger floods. The 50-year flood is little affected by the amount of area that is rendered impervious. *(From Martens, L. A. 1968. U.S. Geological Survey Water Supply Paper 1591C)*

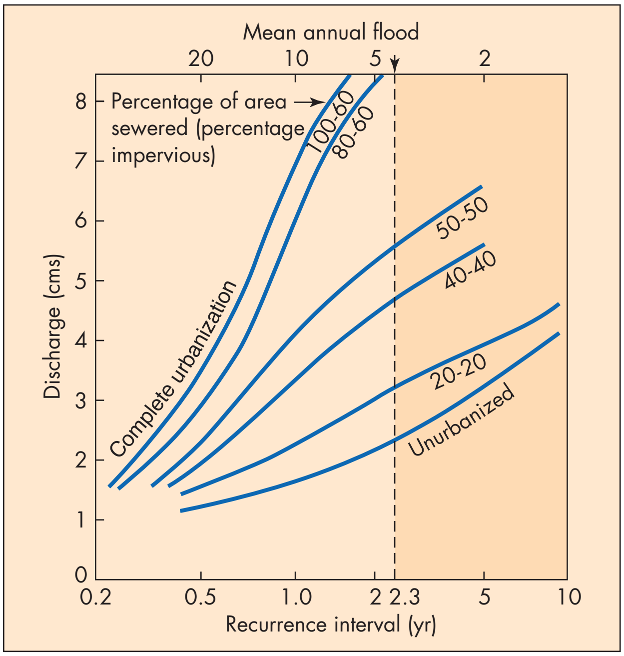


FIGURE 9.21 Urbanization increases flood for a particular recurrence interval Flood frequency curve for a 2.6 km^2 (1 mi^2) basin in various states of urbanization. 100–60 means the basin is 100 percent sewered, and 60 percent of surface area is impervious. The dashed line shows the increase in mean annual flood with increasing urbanization. *(After Leopold, L. B. 1968. U.S. Geological Survey Circular 559)*

Increase in impervious area is not the only type of development that can increase flooding. Some flash floods have occurred because bridges built across small streams block the passage of floating woody debris, causing a wave of water to move downstream when the debris breaks loose. For example, on Friday, June 15, 1990, over 14 cm (5.5 in.) of precipitation fell within approximately 4 hours in some areas of eastern Ohio. Two tributaries of the Ohio River, Wegee and Pipe Creeks, generated flash floods near the small town of Shadyside, killing 21 people and leaving 13 people missing and presumed dead. The floods were described as 5 m (16 ft)-high walls of water that rushed through the valley. In all, approximately 70 houses were destroyed and another 40 were damaged. Trailers and houses were seen washing down the creeks, bobbing like corks in the torrent. The wall of water was apparently due to the failure of debris dams that had developed across the creeks upstream of bridges. Runoff from rainfall had washed debris into the creeks from side slopes; this debris, including tree

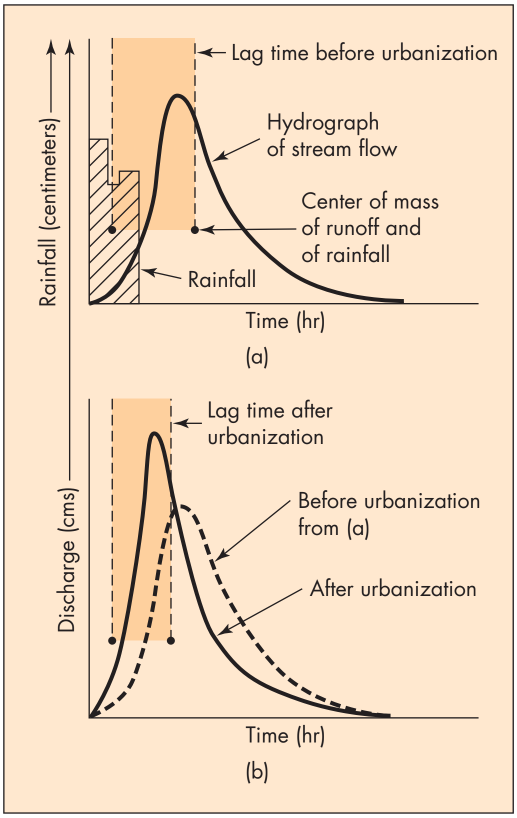


FIGURE 9.22 Urbanization shortens lag time
Generalized hydrographs. (a) Hydrograph shows the typical lag between the time when most of the rainfall occurs and the time when the stream floods. (b) Here, the hydrograph shows the decrease in lag time because of urbanization. *(After Leopold, L. B. 1968. U.S. Geological Survey Circular 559)*

trunks and other material, became lodged against bridges, creating the debris dams. When the bridges could no longer contain the weight of the debris, the dams broke loose, sending surges of water downstream. This scenario has been played and replayed in many flash floods around the world. All too often, the supports for bridges are too close together to allow large debris to pass through; instead, the debris accumulates on the upstream side of the bridge, damming the stream and eventually causing a flood.

9.9 The Nature and Extent of Flood Hazards

Flooding is one of the most frequently experienced natural hazards. In the United States, floods were the number-one type of disaster during the twentieth century, with approximately 100 lives per year (or about 10,000 in the twentieth century) lost because of river flooding. Tragically, this figure is low compared with losses suffered by developing countries that lack monitoring facilities, warning systems, and effective disaster relief.[8,18] **Table 9.1** lists some severe river floods that occurred in the United States from 1937 to 2010.

Factors That Cause Flood Damage

Factors that affect the damage caused by floods include:

- Land use on the floodplain
- Magnitude, or the depth and velocity of the water and frequency of flooding
- Rate of rise and duration of flooding
- Season (e.g., growing season on the floodplain)
- Sediment load deposited
- Effectiveness of forecasting, warning, and emergency systems

Effects of Flooding

The effects of flooding may be primary (i.e., directly caused by the flood) or secondary (i.e., caused by disruption and malfunction of services and systems due to the flood).[18] Primary effects include injury, loss of life, and damage caused by swift currents, debris, and sediment to farms, homes, buildings, railroads, bridges, roads, and communication systems. Erosion and deposition of sediment in the rural and urban landscape may also involve a loss of considerable soil and vegetation. Secondary effects may include short-term pollution of rivers, hunger and disease, and displacement of persons who have lost their homes. In addition, fires may be caused by shorts in electrical circuits or gas mains broken by flooding and associated erosion.[18]

9.10 Adjustments to Flood Hazards

Historically, particularly in the nineteenth century, humans responded to flooding by attempting to prevent the problem; that is, they modified the stream by creating physical barriers, such as

TABLE 9.1 Selected River Floods in the United States

Year	Month	Location	No. of Lives Lost	Property Damage (millions of dollars)
1937	Jan.–Feb.	Ohio and lower Mississippi River basins	137	418
1938	March	Southern California	79	25
1940	Aug.	Southern Virginia and Carolinas and eastern Tennessee	40	12
1947	May–July	Lower Missouri and middle Mississippi River basins	29	235
1951	June–July	Kansas and Missouri	28	923
1955	Dec.	West Coast	61	155
1963	March	Ohio River basin	26	98
1964	June	Montana	31	54
1964	Dec.	California and Oregon	40	416
1965	June	Sanderson, Texas (flash flood)	26	3
1969	Jan.–Feb.	California	60	399
1969	Aug.	James River basin, Virginia	154	116
1971	Aug.	New Jersey	3	139
1972	June	Black Hills, South Dakota (flash flood)	242	163
1972	June	Eastern United States	113	3,000
1973	March–June	Mississippi River	0	1,200
1976	July	Big Thompson River, Colorado (flash flood)	139	35
1977	July	Johnstown, Pennsylvania	76	330
1977	Sept.	Kansas City, Missouri, and Kansas	25	80
1979	April	Mississippi and Alabama	10	500
1983	Sept.	Arizona	13	416
1986	Winter	Western states, especially California	17	270
1990	Jan.–May	Trinity River, Texas	0	1,000
1990	June	Eastern Ohio (flash flood)	21	Several
1993	June–Aug.	Mississippi River and tributaries	50	10,000
1997	January	Sierra Nevada, Central Valley, California	23	Several hundred
2001	June	Houston, Texas. Buffalo Bayou (coastal river)	22	2,000
2006	June–July	Mid-Atlantic states, New York to North Carolina	16	100+
2008	March	Mississippi River and tributaries	24	About 900 (mostly crop loss)
2009	March	Red River	0	24
2010	May	Cumberland River region, Tennessee	30	1,900 (Nashville)
2010	June	Little Missouri River, Arkansas (flash flood)	16	Not reported

dams or levees, or by straightening, widening, and deepening an entire stream so that it would drain the land more efficiently. Every new flood control project has the effect of luring more people to the floodplain in the false hope that the flood hazard is no longer significant. We have yet to build a dam or channel capable of controlling the heaviest runoff, and when the water finally exceeds the capacity of the structure, flooding may be extensive.[18,19]

In recent years, we have begun to recognize the advantages of alternative adjustments to trying to physically prevent flooding. These include flood insurance and controlling the land use on floodplains. We will discuss each of the main adjustments with the realization that no one adjustment is best in all cases. Rather, an integrated approach to minimizing the flood hazard that incorporates the appropriate adjustments for a particular situation is preferable.

The Structural Approach

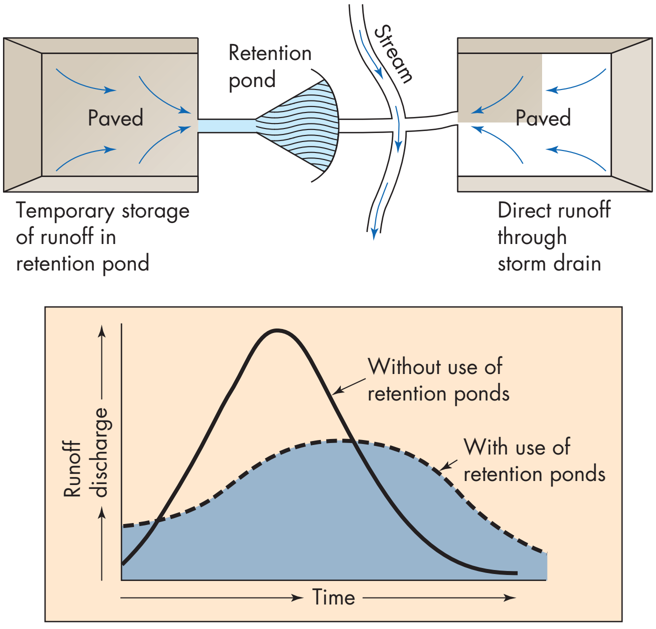
Physical Barriers. Measures to prevent flooding include construction of physical barriers, such as levees (**Figure 9.23**) and floodwalls, which are usually constructed of concrete as opposed to earthen levees; reservoirs to store water for later release at safe rates; and on-site stormwater retention basins (**Figure 9.24**). Unfortunately, the potential benefits of physical barriers are often lost because of increased development on floodplains that are supposedly protected by these structures. For example, the winters of 1986 and 1997 brought tremendous storms and flooding to the western states, particularly California, Nevada, and Utah. In all, damages exceeded several hundred million dollars, and several people died. During one of the storms and floods in 1986, a levee broke on the Yuba River in California, causing more than 20,000 people to flee their homes. An important lesson learned during this flood is that levees constructed along rivers many years ago are often in poor condition and subject to failure during floods.

The 1997 floods damaged campsites and other development in Yosemite National Park. As a result, the park revised its floodplain management policy; some camping and other facilities were abandoned, and the river is now allowed to "run free" along more of its course through the valley.

Some engineering structures designed to prevent flooding have actually increased the flood hazard in the long term. For example, floodwalls produced a bottleneck at St. Louis that increased upstream flooding during the 1993 floods of the Mississippi River. (See A Closer Look: Mississippi River Flooding, 1973 and 1993.)

Recurring flooding, particularly on the Mississippi, has led to controversial speculation that human activities have contributed to an increase in flooding. Over

FIGURE 9.23 Mississippi River levee A levee with a road on top of it protects the bank (left side of photograph) of the lower Mississippi River at this location in Louisiana. *(Comstock Images)*




(b)

FIGURE 9.24 Retention pond (a) Comparison of runoff from a paved area through a storm drain with runoff from a paved area through a temporary storage site (i.e., retention pond). Notice that the paved area drained by way of the retention pond produces a lesser peak discharge and, therefore, is less likely to contribute to flooding of the stream. *(Modified after U.S. Geological Survey Professional Paper 950)* (b) Photograph of a retention pond near Santa Barbara, California. *(Edward A. Keller)*

time, equal flood discharge is producing higher flood stages. The systems of levees, floodwalls, and structures to improve river navigation for barges transporting goods downriver control the smaller floods. For the largest floods, these same systems may constrain or retard flow (i.e., slow it down), and this results in higher levels of flood flow (stage).[20]

After observing causes and effects of many floods, we have learned that structural controls must go hand in hand with floodplain regulations if the hazard is to be minimized.[19,21,22]

Channelization. Straightening, deepening, widening, clearing, or lining existing stream channels are all methods of **channelization**. Basically, it is an engineering technique with the objectives of controlling floods, draining wetlands, controlling erosion, and improving navigation.[29] Of the four objectives, flood control and drainage improvement are the two most often cited in channelization projects. Thousands of kilometers of streams in the United States have been modified, and thousands of kilometers of channelization are now being planned or constructed. Federal agencies alone have carried out several thousand kilometers of channel modification. In the past, however, inadequate consideration has been given to the adverse environmental effects of channelization.

Opponents of channelizing natural streams emphasize that the practice is antithetical to the production of fish and wetland wildlife, and, furthermore, channelizing causes a stream to suffer from extensive aesthetic degradation. The argument is as follows:

- Drainage of wetlands adversely affects plants and animals by eliminating habitats necessary for the survival of certain species.
- Cutting trees along the stream eliminates shading and cover for fish and exposes the stream to the sun; the exposure results in damage to plant life and heat-sensitive aquatic organisms.
- Cutting hardwood trees on the floodplain eliminates the habitats of many animals and birds, while facilitating erosion and siltation of the stream.
- Straightening and modifying the streambed destroys both the diversity of flow patterns

A Closer Look

Mississippi River Flooding, 1973 and 1993

In 1973, spring flooding of the Mississippi River caused the evacuation of tens of thousands of people as thousands of square kilometers of farmland were inundated throughout the Mississippi River Valley. Fortunately, there were few deaths, but the flooding resulted in approximately $1.2 billion in property damage.[23] The 1973 floods occurred despite a tremendous investment in upstream flood-control dams on the Missouri River. Reservoirs behind these dams inundated some of the most valuable farmland in the Dakotas, and, despite these structures, the flood near St. Louis was record breaking.[24] Impressive as this flood was at the time, it did not compare either in magnitude or in the suffering it caused with the flooding that occurred 20 years later.

During the summer of 1993, the Mississippi River and its tributaries experienced one of the largest floods of the century. There was more water than during the 1973 flood, and the recurrence interval exceeded 100 years. The floods lasted from late June to early August and caused 50 deaths and more than $10 billion in property damages. In all, about 55,000 km^2 (21,236 mi^2), including numerous towns and farmlands, were inundated with water.[25,26]

The 1993 floods resulted from a major climatic anomaly that covered the upper Midwest and north-central Great Plains, precisely the area that drains into the Mississippi and lower Missouri River systems.[27] The trouble began with a wet autumn and a heavy spring snowmelt that saturated the ground in the upper Mississippi River basin. Then, early in June, a high-pressure center became stationary on the East Coast, drawing moist, unstable air into the upper Mississippi River drainage basin. This condition kept storm systems in the Midwest from moving east. At the same time, air moving in over the Rocky Mountains initiated unusually heavy rainstorms.[27] The summer of 1993 was the wettest on record for Illinois, Iowa, and Minnesota. For example, Cedar Rapids, Iowa, received about 90 cm (35 in.) of rain from April through July—the equivalent of a normal year's rainfall in just 4 months![26] Intense precipitation falling on saturated ground led to a tremendous amount of runoff and unusually large floods during the summer. The floodwaters were high for a prolonged time, putting pressure on the flood defenses of the Mississippi River, particularly **levees**, which are earth embankments constructed parallel to the river to contain floodwaters and reduce flooding (**Figure 9.F**). Levees are constructed on the flat land adjacent to the river known as the floodplain.

Before construction of the levees, the Mississippi's floodplain, flat land adjacent to the river that periodically floods, was much wider and contained extensive wetlands. Since the first levees were built in 1718, approximately 60 percent of the wetland in Wisconsin, Illinois, Iowa, Missouri, and Minnesota—all hard hit by the flooding in 1993—have been lost. In some locations, such as St. Louis, Missouri, levees give way to floodwalls designed to protect the city against high-magnitude floods. Examination of **Figure 9.G**, a satellite image from mid-July 1993, shows that the river is narrow at St. Louis, where it is contained by the floodwalls, and broad upstream near Alton, where extensive flooding occurred. The floodwalls produce a bottleneck because water must pass through a narrow channel between the walls; the floodwaters get backed up waiting to get through. These floodwaters contributed to the 1993 flooding upstream of St. Louis (Figure 9.G).

Despite the high walls constructed to prevent flooding, the rising flood peak came to within about 0.6 m (2 ft) of overtopping the floodwalls at St. Louis. Failure of levees downstream from St. Louis partially relieved the pressure, possibly saving the city from flooding. Levee failures (**Figure 9.H**) were very common during the flood event.[26,27] In fact, almost 80 percent of the private levees—that is, levees built by farmers and homeowners—along the Mississippi River and its tributaries failed.[26] However, most of the levees built by the federal government survived the flooding and undoubtedly saved lives and property. Unfortunately, there is no uniform building code for the levees, so some areas have levees that are higher or lower than others. Failures occurred as a result of overtopping and breaching, or rupturing, resulting in massive flooding of farmlands and towns (**Figure 9.I**).[26]

One of the lessons learned from the 1993 floods is that construction of levees provides a false sense of security. It is difficult to design levees to withstand extremely high-magnitude floods for a long period of time. Furthermore, the loss of wetlands allows for less floodplain space to "soak up" the floodwaters.[28] The 1993 floods caused extensive damage and loss of property; in

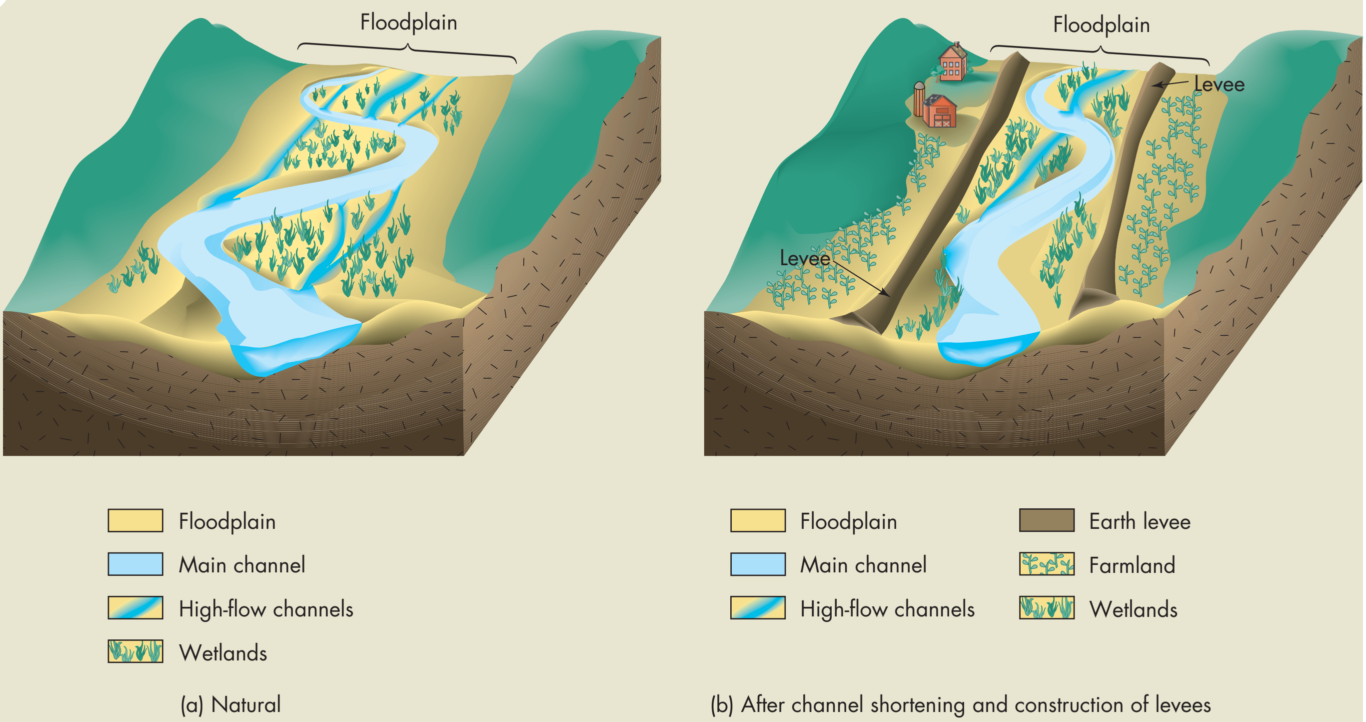


FIGURE 9.F Floodplain with and without levees (a) Idealized diagram of natural floodplain (flat land adjacent to the river produced by the river) with wetlands. (b) Floodplain after channel is shortened and levees are constructed. Land behind levees is farmed, and wetlands are generally confined between the levees.

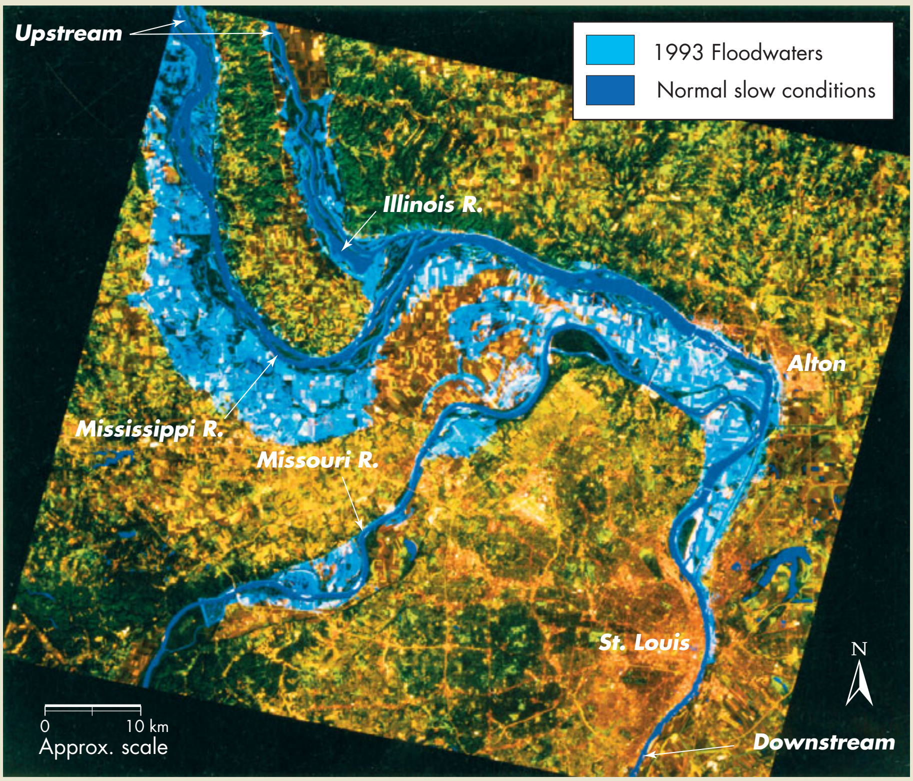


FIGURE 9.G Mississippi River flood of 1993 This image shows the extent of flooding from the 1993 Mississippi River floods. In the lower-right corner, the river becomes narrow where it flows by the city of St. Louis, Missouri (orange area in lower-right corner). The river is narrow here because flow is constricted by a series of floodwalls constructed to protect the city. Notice the extensive flooding upstream of St. Louis, Missouri. The city with its floodworks is a real bottleneck to the flow of water. The town of Alton, Illinois, is the first orange area upstream from St. Louis. This city has a notorious history of flooding. *(Cindy Brown/Corbis)*

FIGURE 9.H Levee failure Failure of this levee in Illinois during the 1993 floods of the Mississippi River caused flooding in the town of Valmeyer. *(Comstock Images)*

1995, floodwaters of the Mississippi River system inundated floodplain communities once again. Several communities along the river are rethinking strategies concerning the flood hazard and are moving to higher ground! Of course, this is exactly the adjustment that is appropriate.

FIGURE 9.I Damaged farmland Damage to farmlands during the peak of the 1993 flood of the Mississippi River. *(Comstock Images)*

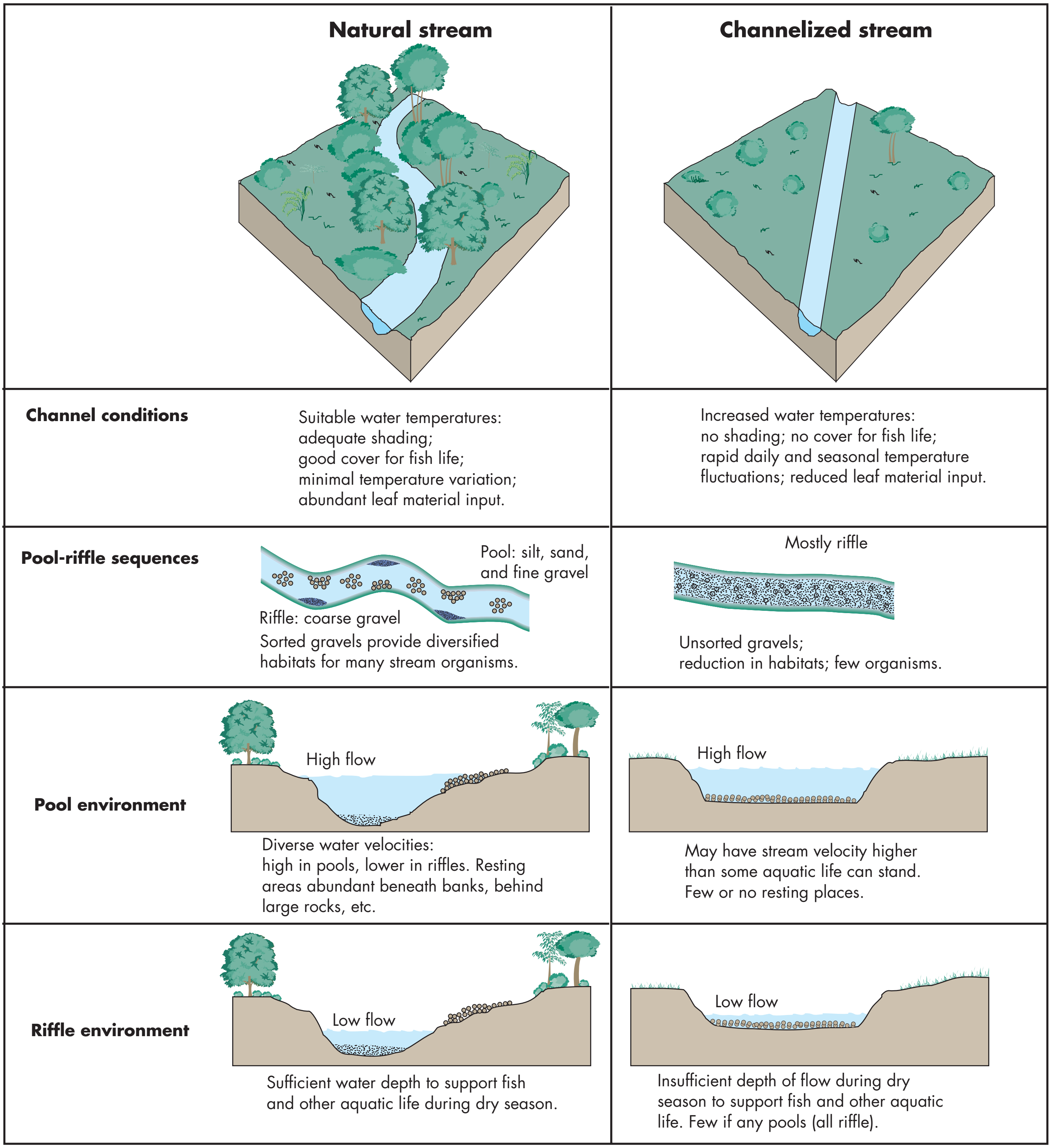


FIGURE 9.25 Natural versus channelized stream A natural stream compared with a channelized stream in terms of general characteristics and pool environments. *(Modified after Corning, Virginia Wildlife, February 1975)*

and the feeding and breeding areas for aquatic life while changing peak flow.

- Conversion of wetlands from a meandering stream to a straight, open ditch seriously degrades the aesthetic value of a natural area.[29] **Figure 9.25** summarizes some of the differences between natural streams and those modified by channelization.

Not all channelization causes serious environmental degradation; in many cases, drainage projects are beneficial. Benefits are probably best observed in urban areas subject to flooding and in rural areas where previous land use has caused drainage problems. In addition, there are other examples in which channel modification has improved navigation or reduced flooding and has not caused environmental disruption.

Channel Restoration: Alternative to Channelization

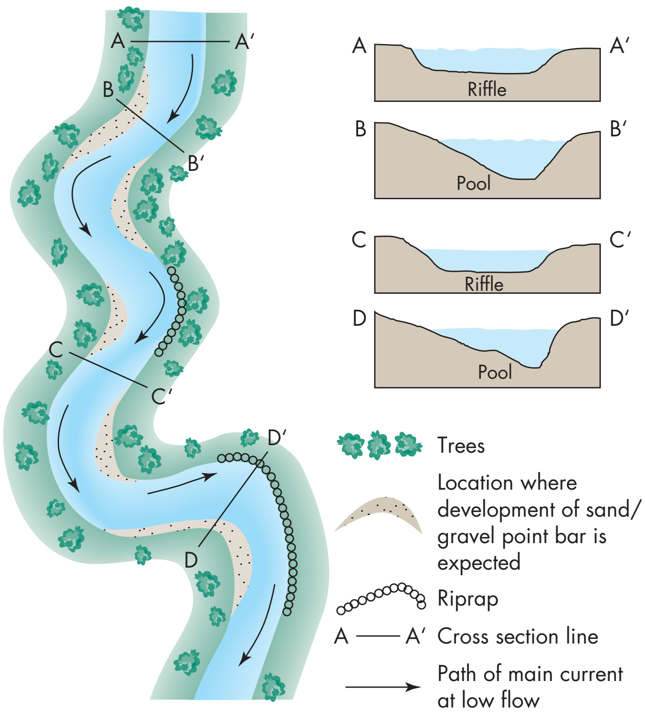
Many streams in urban areas scarcely resemble natural channels. The process of constructing roads, utilities, and buildings with the associated sediment production is sufficient to disrupt most small streams. **Channel restoration**[30] uses various techniques: Cleaning urban waste from the channel, allowing the stream to flow freely, protecting the existing channel banks by not removing existing trees or, where necessary, planting additional native trees and other vegetation. Trees provide shade for a stream, and the root systems protect the banks from erosion (**Figure 9.26**). The objective is to create a more natural channel by allowing the stream to meander and, when possible, provide for variable, low-water flow conditions: fast and shallow flow on riffles alternating with slow and deep flow in pools. Where lateral bank erosion must be absolutely controlled, the outsides of bends may be defended with large stones known as *riprap*. Design criteria for channel restoration are shown in **Figure 9.27**.

River restoration of the Kissimmee River in Florida may be the most ambitious restoration project ever attempted in the United States (see Chapter 4).[31] In Los Angeles, California, a group called Friends of the River has suggested that the Los Angeles River be restored. This will be a difficult task, since most of the riverbed and banks are lined with concrete (**Figure 9.28**, page 317). However, a river park is planned for one section of the river where a more natural-looking channel has reappeared since channelization (**Figure 9.29**, page 317).

Flood Insurance

In 1968, when private companies became reluctant to continue to offer flood insurance, the federal government took over. The U.S. National Flood Insurance Program makes, with restrictions including a 30-day waiting period, flood insurance available at subsidized rates. Special Flood Hazard Areas, those inundated by the 100-year flood, are

FIGURE 9.26 Tree roots protecting stream bank from erosion *(Edward A. Keller)*



(a)

(b)

FIGURE 9.27 Urban stream restoration (a) Channel-restoration design criteria for urban streams, using a variable channel shape to induce scour and deposition (pools and riffles) at desired locations. *(Modified after Keller, E. A., and Hoffman, E. K. 1977. Urban streams: sensual blight or amenity.* Journal of Soil and Water Conservation *32(5):237–240)* (b) Placing riprap where absolutely necessary to defend the bank, Briar Creek, Charlotte, North Carolina. Notice the planting of grass on banks with straw mulch and trees growing on banks. *(Edward A. Keller)*

designated, and new property owners must buy insurance at rates determined on the basis of the risk. The insurance program is intended to provide short-term financial aid to victims of floods as well as to establish long-term land-use regulations for the nation's floodplains. The basic risk evaluation centers on identifying the floodplain area inundated by the 100-year flood. Only flood-proofed buildings are allowed in this area (**Figure 9.30**, page 318), and no construction is allowed on the portion of the floodplain inundated by the 20-year flood. For a community to join the National Flood Insurance Program, it must adopt minimum standards of land-use regulation within the 100-year floodplain, mapped by the Federal Emergency Management Agency (FEMA). Nearly all communities with a flood risk in the United States have basic flood hazard maps and have initiated some form of floodplain regulations. Several million insurance policies are presently held by property owners.[32]

By the early 1990s, it was recognized that the insurance program was in need of reform, resulting in the National Flood Insurance Reform Act of 1994. The act was passed to encourage opportunities to mitigate flood hazards, including flood-proofing, relocations, and buy-outs of properties likely to be frequently flooded.[32]

Flood-Proofing

There are several methods of flood-proofing. The most common include:

- Raising the foundation of a building above the flood hazard level by using piles or columns or by extending foundation walls or earth fill[32]
- Constructing floodwalls or earth berms around buildings to seal them from floodwaters
- Using waterproofing construction, such as waterproofed doors and waterproofed basement walls and windows
- Installing improved drains with pumps to keep flood waters out

(a)

(b)

FIGURE 9.28 Channelization versus restoration (a) Concrete channel in Los Angeles River system compared with (b) channel restoration in North Carolina. *(Edward A. Keller)*

FIGURE 9.29 Los Angeles River Part of the Los Angeles River where a more natural channel has developed since channelization. *(Ambient Images Inc/Alamy)*

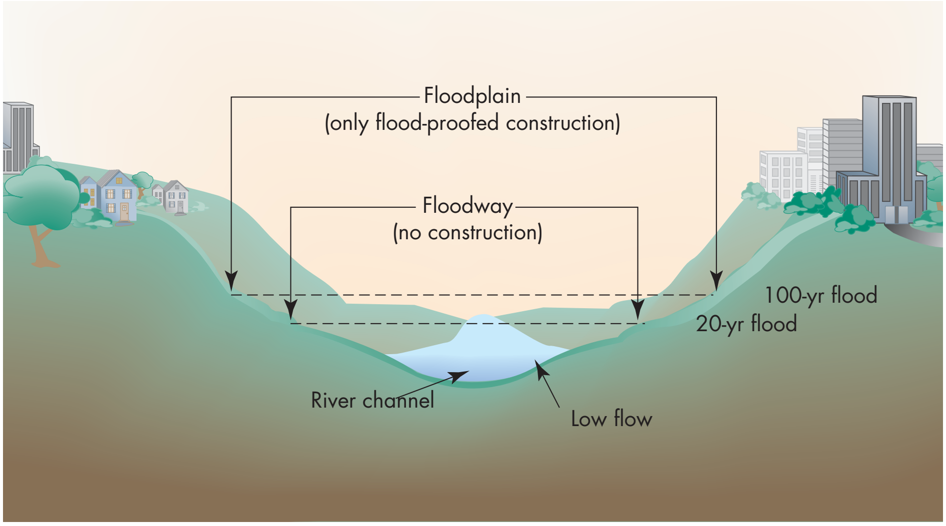


FIGURE 9.30 Floodplain regulation Idealized diagram showing areas inundated by the 100- and 20-year floods used in the U.S. National Flood Insurance Program.

There are also modifications to buildings that are designed to minimize flood damages while allowing floodwaters to enter a building. For example, ground floors along expansive riverfront properties in some communities in Germany are designed so that they are not seriously damaged by floodwaters and may be easily cleaned and made ready for reuse after a flood.[32]

Floodplain Regulation

Previously, we have defined the floodplain as a landform produced by a river. When we try to regulate development on a flood-hazard area, we often define the floodplain from a hydrologic point of view. Thus, the 100-year floodplain is that part of a river valley that is inundated by the 100-year flood. For a particular river at a particular site, that flood has a discharge (i.e., volume of flow per unit time such as cubic meters or cubic feet per second). We often determine that discharge by analyzing past flow records (see A Closer Look: Magnitude and Frequency of Floods).

From an environmental point of view, the best approach to minimizing flood damage in urban areas is **floodplain regulation**. The big problem is that several million people in nearly 4,000 U.S. towns and cities live on floodplains facing a recognized flood hazard. The objective of floodplain regulation is to obtain the most beneficial use of floodplains while minimizing flood damage and the cost of flood protection.[33] Floodplain regulation is a compromise between indiscriminate use of floodplains, resulting in loss of life and tremendous property damage, and complete abandonment of floodplains, which gives up a valuable natural resource.

This is not to say that physical barriers, reservoirs, and channelization are not desirable. In areas developed on floodplains, they will be necessary to protect lives and property. We need to recognize, however, that the floodplain belongs to the river system, and any encroachment that reduces the cross-sectional area of the floodplain increases flooding (**Figure 9.31**). An ideal solution would be discontinuing floodplain development that necessitates new physical barriers. In other words, the ideal is to "design with nature." Realistically, the most effective and practical solution in most cases will be using a combination of physical barriers and floodplain regulations that results in fewer physical modifications of the river system. For example, reasonable floodplain zoning in conjunction with a diversion channel project or upstream reservoir may result in a smaller diversion channel or reservoir than would be necessary without floodplain regulations.

Flood-Hazard Mapping

A preliminary step to floodplain regulation is flood-hazard mapping, which is a means of providing

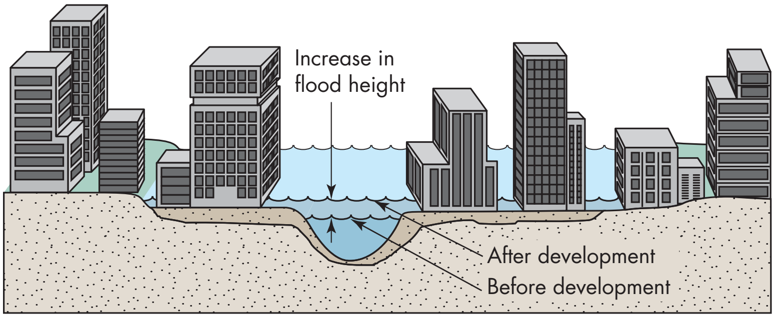


FIGURE 9.31 Increasing flood hazard Development that encroaches on the floodplain can increase the heights of subsequent floods. *(From Water Resources Council. 1971. Regulation of Flood Hazard Areas, vol. 1)*

FIGURE 9.32 Scour marks indicate flood height Floodwaters of the San Gabriel River in Los Angeles County, California, removed bark from the roots and lower trunk of these trees. Hydrologists measured the elevation of the top of the scour marks to determine the height of the 2005 flood on this segment of the river. *(Courtesy of T. Carpenter)*

information about a floodplain for land-use planning.[34] Flood-hazard maps may delineate past floods or floods of a particular frequency, such as the 100-year flood (Figure 9.30). They are useful in regulating private development, purchasing land for public use as parks and recreational facilities, and creating guidelines for future land use on floodplains.

Flood-hazard evaluation may be accomplished in a general way by direct observation and measurement of physical parameters. For example, extensive flooding of the Mississippi River Valley during the summer of 1993 is clearly shown on images produced from satellite-collected data (see Figure 9.G). Floods can also be mapped from aerial photographs taken during flood events; they can be estimated from high-water lines, flood deposits, scour marks (Figure 9.32), and trapped debris on the floodplain, measured in the field after the water has receded.[35] The most common way we produce flood-hazard maps today is to use mathematical models that show the land flooded by a particular flow—often the 100-year flood.

Floodplain Zoning. Flood-hazard information is used to designate a flood-hazard area. Once the hazard area has been established, planners can establish zoning regulations and acceptable land use. Figure 9.33 shows a typical zoning map before and after establishment of floodplain regulations.

Relocating People from Floodplains: Examples from North Carolina and North Dakota

For several years, state and federal governments have been selectively purchasing homes damaged by floodwaters. The purpose is to remove homes from hazardous areas and thereby reduce future losses. In September 1999, Hurricane Floyd brought nearly 50 cm (20 in.) of rain to the North Carolina region, flooding many areas. State and federal governments decided to spend nearly $50 million to remove about 430 homes in Rocky Mount, North Carolina.

At Churchs Ferry, North Dakota, there has been a wet cycle since 1992, causing nearby Devils Lake to rise approximately 8 m (26 ft). The lake has no outlet, and this part of the Northern Plains is very flat. As a result, the lake has more than doubled in area and is inundating the land in the vicinity of Churchs Ferry. By late June 2000, the town was all but deserted; the population of the town shrank from approximately 100 to 7 people. Most of the people in the town have taken advantage of a voluntary federal buyout plan and have moved to higher ground, many to the town of Leeds, approximately 24 km (15 mi) away. The empty houses left behind will be demolished or moved to safer ground.

The lucrative buyout of $3.5 million seemed to be assured, a "slam dunk." The people who participated in the buyout program were given the appraised value of their homes plus an incentive; most considered the offer too good to turn down. There was also recognition that the town would eventually have come to an end as a result of flooding. Nevertheless, there was some bitterness among the town's population, and not everyone participated. The mayor and the fire chief of the town are among the seven people who decided to stay. The buyout program for Churchs Ferry demonstrated that the process is an emotional one; it is difficult for some people to make the decision to leave their home, even though they know it is likely to be damaged by floodwaters in the relatively near future.

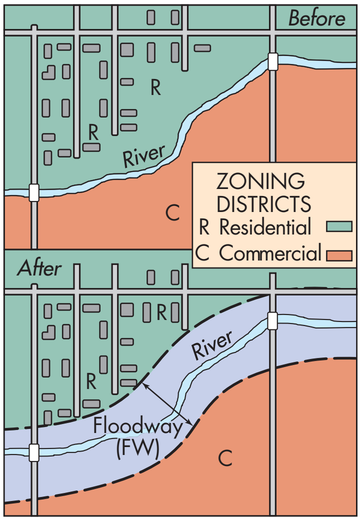


FIGURE 9.33 Floodplain zoning Typical zoning map before and after the addition of flood regulations. *(From Water Resources Council. 1971. Regulation of Flood Hazard Areas, vol. 1)*

Personal Adjustment: What to Do and What Not to Do

Flooding is the most commonly experienced natural hazard. Although we cannot prevent floods from happening, individuals can be better prepared. **Table 9.2** summarizes what individuals can do to prepare for a flood as well as what not to do.

9.11 Perception of Flooding

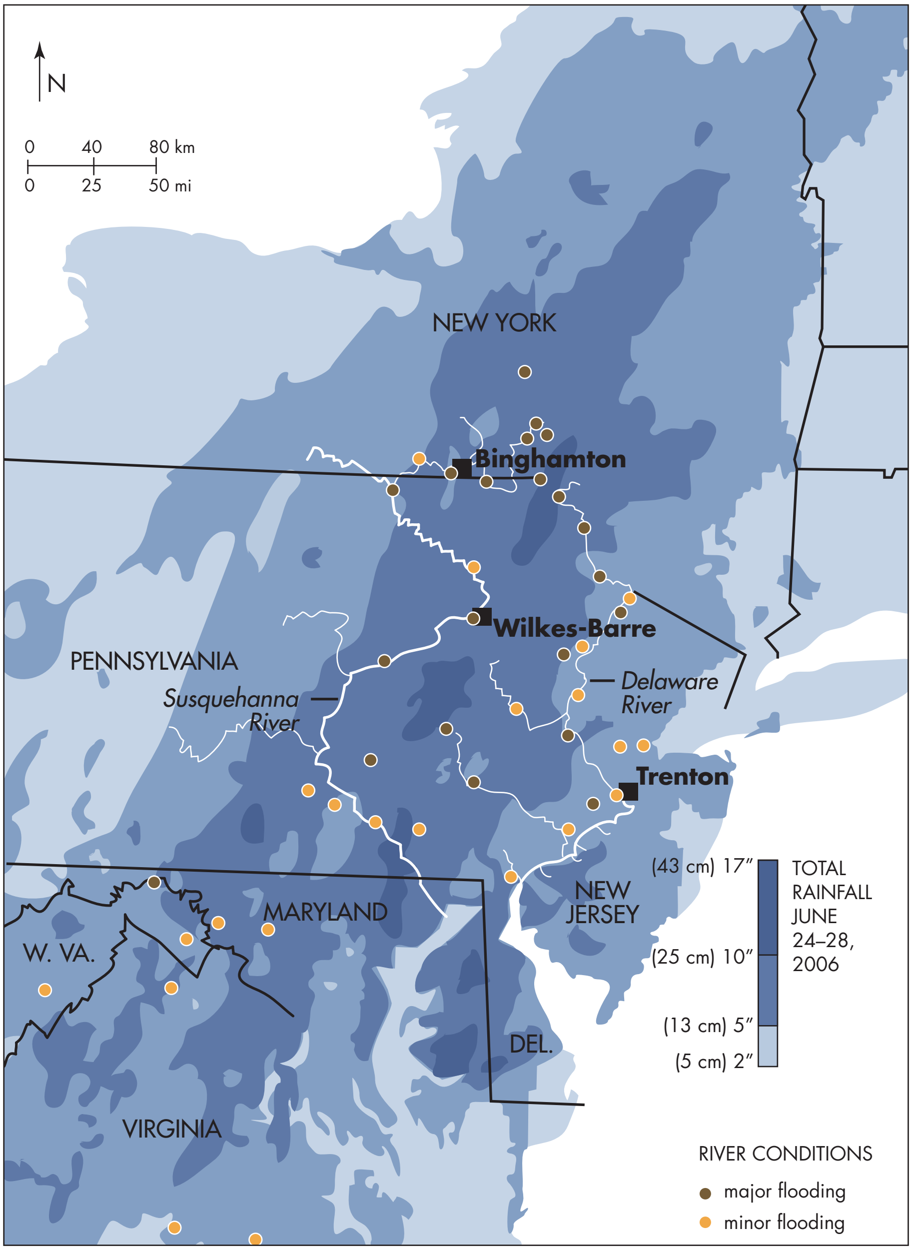
At the institutional level—that is, at the government and flood-control agency level—perception and understanding of flooding are adequate for planning purposes. On the individual level, however, the situation is not as clear. People are tremendously variable in their knowledge of flooding, anticipation of future flooding, and willingness to accept adjustments caused by the hazard.

Progress at the institutional level includes mapping of flood-prone areas (thousands of maps have been prepared), of areas with a flash-flood potential downstream from dams, and areas where urbanization is likely to cause problems in the near future. In addition, the federal government has encouraged states and local communities to adopt floodplain management plans.[4] Still, planning to avoid the flood hazard by not developing on floodplains or by relocating present development to locations off the floodplain needs further consideration and education if it is to be accepted by the general population. This was tragically shown by the 2006 floods in the Mid-Atlantic United States, when severe river flooding impacted the region from Virginia to New York (**Figure 9.34**, page 322). More than 200,000 floodplain residents were evacuated in Pennsylvania alone, and damages exceeding $100 million were incurred. About 16 people lost their lives as cars were swept away by floodwaters and people drowned in flood-swollen creeks and rivers. About 70 people were rescued from rooftops. As a people, we need to just "say no" to future development on floodplains. That is the most cost-effective way to reduce chronic flooding.

TABLE 9.2 What to Do and What Not to Do Before and After a Flood

	Preparing for a Flood
What to Do	• Check with your local flood control agency to see if your property is at risk from flooding.
What to Do	• If your property is at risk, purchase flood insurance if you can and be sure that you know how to file a claim.
What to Do	• Buy sandbags or flood boards to block doors.
What to Do	• Make up a flood kit, including a flashlight, blankets, raingear, battery-powered radio, first-aid kit, rubber gloves, and key personal documents. Keep it upstairs, if possible.
What to Do	• Find out where to turn off your gas and electricity. If you are not sure, ask the person who checks your meter when he or she next visits.
What to Do	• Talk about possible flooding with your family or housemates. Consider writing a flood plan and store these notes with your flood kit.
What Not to Do	• Underestimate the damage a flood can do.
	When You Learn That a Flood Warning Has Been Issued
What to Do	• Be prepared to evacuate.
What to Do	• Observe water levels and stay tuned to radio and television news and weather reports.
What to Do	• Move people, pets, and valuables upstairs or to higher ground.
What to Do	• Move your car to higher ground. It takes only 0.6 m (2 ft) of fast-flowing water to wash away your car.
What to Do	• Check on your neighbors. Do they need help? They may not be able to escape upstairs or may need help moving furniture.
What to Do	• Do as much as you can in daylight. If the electricity fails, it will be hard to do anything.
What to Do	• Keep warm and dry. A flood can last longer than you think, and it can get cold. Take warm clothes, blankets, a Thermos, and food supplies.
What Not to Do	• Walk in floodwater above knee level: It can easily knock you off your feet. Also, manholes, road works, and other hazards may be hidden beneath the water.
	After a Flood
What to Do	• Check house for damage; photograph any damage.
What to Do	• If insured, file a claim for damages.
What to Do	• Obtain professional help in removing or drying carpets and furniture, as well as cleaning walls and floors.
What to Do	• Contact gas, electricity, and water companies. You will need to have your supplies checked before you turn them back on.
What to Do	• Open doors and windows to ventilate your home.
What to Do	• Wash water taps and run them for a few minutes before use. Your water supply may be contaminated; check with your water supplier if you are concerned.
What Not to Do	• Touch items that have been in contact with the water. Floodwater may be contaminated and could contain sewage. Disinfect and clean thoroughly everything that got wet.

Modified after Environment Agency, United Kingdom, www.environment_agency.gov.uk/flood/press_2.htm. Accessed 11/1/00.



(a)

FIGURE 9.34 Mid-Atlantic floods of June–July 2006 (a) Map of major and minor flooding. *(Modified from New York Times with data from National Weather Service)* (b) Collecting mail from a flooded home in Wilkes-Barre, Pennsylvania. *(Matt Rourke/AP Photo)*

(b)

Making The Connection

Linking the Opening Case History About the Pakistan Floods of 2010 to the Fundamental Concepts

Consider and discuss the following questions:

1. What was the role of human population and land use in the Pakistan flooding?
2. How are science and values linked to reducing the flood hazard in Pakistan?
3. How might sustainability of Pakistan be linked to the flood hazard in the country?
4. What can be learned from the flooding in Pakistan that is applicable to other countries in Asia?

Summary

Streams and rivers form a basic transport system of the rock cycle and are a primary erosion agent shaping the landscape. The region drained by a stream system is called a drainage basin.

Sediments deposited by lateral migration of meanders in a stream and by periodic overflow of the stream banks form a floodplain. The magnitude and frequency of flooding are inversely related and are functions of the intensity and distribution of precipitation, the rate of infiltration of water into the soil and rock, and topography. Flash floods are produced by intense, brief rainfall over a small area. Downstream floods in major rivers are produced by storms of long duration over a large area that saturate the soil, causing increased runoff from thousands of tributary basins. Urbanization has increased flooding in small drainage basins by covering much of the ground with impermeable surfaces, such as buildings and roads that increase the runoff of stormwater.

River flooding is the most universally experienced natural hazard. Loss of life is relatively low in developed countries that have adequate monitoring and warning systems, but property damage is much greater than in preindustrial societies because floodplains are often extensively developed. Factors that control damage caused by flooding include land use on the floodplain; the magnitude and frequency of flooding; the rate of rise and duration of the flooding; the season; the amount of sediment deposited; and the effectiveness of forecasting, warning, and emergency systems.

Environmentally, the best solution to minimizing flood damage is floodplain regulation, but it will remain necessary to use engineering structures to protect existing development in highly urbanized areas. These include physical barriers such as levees and floodwalls and structures that regulate the release of water, such as reservoirs. The realistic solution to minimizing flood damage involves a combination of floodplain regulation and engineering techniques. The inclusion of floodplain regulation is critical because engineered structures tend to encourage further development of floodplains by producing a false sense of security. The first step in floodplain regulation is mapping the flood hazards, which can be difficult and expensive. Planners can then use the maps to zone a flood-prone area for appropriate uses. In some cases, homes in flood-prone areas have been purchased and demolished by the government, and people have relocated to safe ground.

Channelization is the straightening, deepening, widening, cleaning, or lining of existing streams. The most commonly cited objectives of channelization are flood control and drainage improvement. Channelization has often caused environmental degradation, so new projects are closely evaluated. New approaches to channel modification using natural processes are being practiced, and, in some cases, channelized streams are being restored.

An adequate perception of flood hazards exists at the institutional level. On the individual level, however, more public-awareness programs are needed to help people clearly perceive the hazard of living in flood-prone areas.

Revisiting Fundamental Concepts

Human Population Growth
More and more people are living on floodplains. These flat lands adjacent to rivers, which have a high flood risk, are seen by too many people as a place to develop. To end this folly, we must be firm in establishing floodplain regulation and just say no to most floodplain development.

Sustainability Rivers are the lifeblood of the land. They provide water resources and routes for the transport of people and goods, and they maintain important ecosystems, from wetlands to floodplains. Building a sustainable future is not possible without planning for sustainable rivers.

Earth as a System Rivers are one of the land's major systems. They transport water and sediment while eroding the land to form most of our landscape. Over time, rivers change as a result of land use, such as conversion of forest lands for urban and agricultural purposes. These changes have increased the flood hazard by (1) filling channels in agricultural regions with sediment eroded from the land, which also depletes soils, and (2) increasing runoff in urban areas, producing more and larger floods, while decreasing infiltration of water into the soil.

Hazardous Earth Processes, Risk Assessment, and Perception Flooding is the most universally experienced hazard. It is also a hazard for which the risks are well known. A major problem is convincing people and communities that unwise land use on floodplains will lead to flood losses. The key is to educate people so that they gain a better understanding of the flood hazard and of where and why floods occur: in other words, heighten the public perception of flooding.

Scientific Knowledge and Values The science of rivers, including their ecology and hydrology, is well advanced. However, our values often conflict with science when it comes to reducing the flood hazard. Often, we choose a "technology fix" to build more flood-control dams, higher levees, more floodwalls, or to channelize rivers. These practices have damaged river ecosystems and have lured people to encroach on floodplains, leading to even greater flood losses. Floodplain management and river restoration reflect the value we place on rivers as a resource to be revered, not degraded.

Key Terms

channel pattern (p. 297)
channel restoration (p. 315)
channelization (p. 310)
continuity equation (p. 292)
discharge (p. 292)
downstream flood (p. 303)
drainage basin (p. 290)
flash flood (p. 299)
flooding (p. 298)
floodplain (p. 290)
floodplain regulation (p. 318)
levee (p. 309)
river (p. 290)
runoff (p. 290)

Review Questions

1. Define *drainage basin*.
2. What are the three components that make up the total load a stream carries?
3. What is the continuity equation?
4. What were the lessons learned from the 1992 flood of the Ventura River?
5. Differentiate between *competency* and *capacity*.
6. Differentiate between *braided* and *meandering channels*.
7. What is the riverine environment?
8. Differentiate between *pools* and *riffles*.
9. Differentiate between *upstream* and *downstream floods*.
10. What do we mean when we say a 10-year flood has occurred?
11. How does urbanization affect the flood hazard?
12. What are the major factors that control damage caused by floods?
13. What are the primary and secondary effects of flooding?
14. What do we mean by floodplain regulation?
15. Define *channelization*.
16. What is channel restoration?

Critical Thinking Questions

1. You are a planner working for a community that is expanding into the headwater portions of drainage basins. You are aware of the effects of urbanization on flooding and want to make recommendations to avoid some of these effects. Outline a plan of action.
2. You are working for a county flood-control agency that has been channelizing streams for many years. Although bulldozers are usually used to straighten and widen the channel, the agency has been criticized for causing extensive environmental damage. You have been asked to develop new plans for channel restoration to be implemented as a stream-maintenance program. Devise a plan of action that would convince the official in charge of the maintenance program that your ideas will improve the urban stream environment and help reduce the potential flood hazard.
3. Does the community you live in have a flood hazard? If not, why not? If there is a hazard, what has been done and/or is being done to reduce or eliminate the hazard? What more could be done?

Companion Website

www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Landslide A La Conchita, California, landslide in 2005 destroyed 13 homes and killed 10 people. *(AP Photo)*

10

Slope Processes, Landslides, and Subsidence

Learning Objectives

Landslides, the movement of materials down slopes, constitute a serious natural hazard in many parts of the United States and the rest of the world. Landslides are often linked to other hazards, such as earthquakes and volcanoes. Most landslides are small and slow, but a few are large and fast. Both types may cause significant loss of life and damage to human property, particularly in urban areas. In this chapter, we focus on the following learning objectives:

- **Understand basic slope processes and the causes of slope failure**
- **Understand the role of driving and resisting forces on slopes and how they are related to slope stability**
- **Understand how slope angle and topography, vegetation, water, and time affect both slope processes and the incidence of landslides**
- **Understand how human use of the land has resulted in landslides**
- **Know methods of identification, prevention, warning, and correction of landslides**
- **Understand processes related to land subsidence**

Case History

La Conchita Landslide of 2005

The small beachside community of La Conchita, located about 80 km (50 mi) northwest of Los Angeles, California, was the site of a disaster on January 10, 2005. On that day, a fast-moving landslide damaged or destroyed 36 homes and killed 10 people (**Figure 10.1**). The 2005 landslide was a reactivation of a 1995 landslide that destroyed several homes but caused no deaths. Both the 1995 and 2005 events were, in turn, part of an older prehistoric landslide, less than about 6,000 years old, on the steep slope directly above La Conchita. As we shall see, this 6,000-year-old slide is part of an even older, larger prehistoric slide on the mountain above.

The winter of 2004–2005 was particularly wet, with high-intensity rainfall occurring at times. Neither residents nor local officials recognized that another landslide was imminent. The 2005 debris flow was different from that of 1995 in that the flow was faster, at 45 km/hr (30 mph), and moved further into the community. A number of people were trapped in their homes, while others ran for their lives.

Directly behind the community is a 200 m (600 ft) high slope that produces continuing landslide hazards for humans living below it. La Conchita should never have been constructed at the foot of that slope. It has been known that landslides have occurred in the area for about 100 years. More telling, the community is built on about 15 m (50 ft) of old landslide deposits. Landslides above La Conchita and to the east and west have been occurring for thousands of years, long before people made the decision to build beach homes at the base of the steep slope.

A study of La Conchita and the surrounding area suggests that the debris flows and slides of 1995, 2005, and older events are a part of a much larger prehistoric landslide less than about 40,000 years old that had not been recognized at the time of the more recent events (**Figure 10.2**). There is no evidence that the much larger, older prehistoric slide is moving as a mass, but parts are active, especially at the western margin of the slide.[1]

It is not a matter of *if*, but *when*, future landslides will occur on the slopes above La Conchita. No part of the La Conchita community is exempt from a future landslide.[2]

A potential solution to reduce the hazard to people and houses is to transform the land use of La Conchita from an area where people live into a coastal park. Not all people living there would be happy to hear such a suggestion, but society could help relocate people with fair compensation for valuable coastal property. The

FIGURE 10.1 Earthflow buries people, houses, and cars The toe of the 2005 La Conchita landslide, shown here, buried at least 10 people and damaged or destroyed 30 houses. When this mass of mud and debris flowed at a velocity of about 10 m/sec (30 ft/sec) into and over these homes, it had the consistency of thick concrete pouring out of a cement truck. *(Edward A. Keller)*

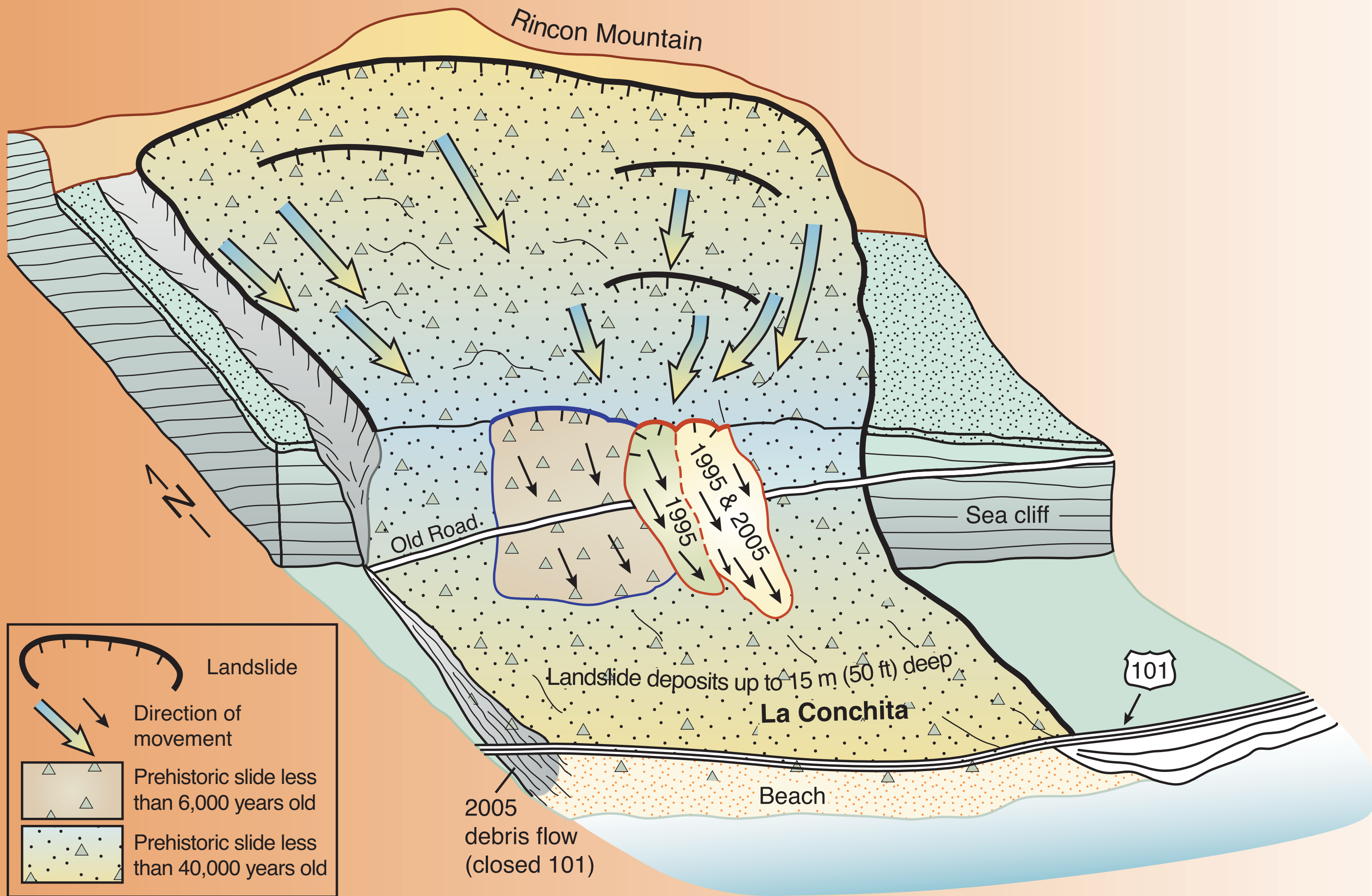


FIGURE 10.2 Idealized diagram of landslides at La Conchita, California The fast-moving landslides of 1995 and 2005 are a reactivation of part of a larger prehistoric slide that is less than 6,000 years old, which is part of a much larger, older (few tens of thousands of years) landslide called the Rincon Mountain landslide.

result would be a transformation of a hazardous site into a resource for future generations. At the least, we need to be diligent in the future concerning land use planning and avoid unwise development on the large prehistoric slide above La Conchita. A similar, but smaller, prehistoric slide was reactivated in Malibu, California, in the mid-1980s, causing claimed damages of about $200 million.

A report with recommendations was commissioned by the state of California concerning the landslide hazard on the slope directly behind La Conchita (i.e., the slides that occurred in 1995 and 2005).[3] The report discusses several options from the perspective of risk assessment and cost. Total risk exposure over the next 50 years is about $190 million, with certain loss of life if nothing is done. A complete grading of the slope above La Conchita (i.e., removal/remolding of slope materials and slope reduction to a lower angle) would cost about $200 million, and (according to the report) would reduce the risk to a tolerable level. A more focused grading project to include the slides of 1995 and 2005 would cost about $50 million and would also (according to the report) lower the risk to a tolerable level. With both of the grading options, there is still the risk of damages and loss of life in the future. The option of risk avoidance (i.e., moving homes out of harm's way) was also discussed in the report. Risk avoidance would cost about $50 million (to purchase homes) and is the most likely option to prevent future loss of life. However, the option that appears to be the one most seriously considered is the more focused grading of the slide masses of 1995 and 2005.This option is not without risk, but it does allow for the La Conchita community to continue its somewhat uncertain history.

What has been learned so far at La Conchita is that both prehistoric and active landslides can be recognized and their future activity evaluated. We now need to be proactive and take steps to reduce risk from future landslides.

10.1 Introduction to Landslides

Landslides and related phenomena cause substantial damage (**Figure 10.3**) and loss of life. In the United States, between 25 and 50 people are killed each year by landslides. This number increases to between 100 and 150 if collapses of trenches and other excavations are included. The total annual cost of damages is about $3.5 billion.[4]

Landslides and other types of ground failure are natural phenomena that would occur with or without human activity. However, human land use has led to an increase in these events in some situations and a decrease in others. For example, landslides may occur on previously stable hillsides that have been modified for housing development; on the other hand, landslides on naturally sensitive slopes are sometimes averted through the use of stabilizing structures or techniques.

FIGURE 10.3 Homes destroyed Aerial photograph of the lower part of the Portuguese Bend landslide in southern California (1950s). Note the kink in the pier near the end of the landslide. Eventually, most of the homes as well as the swim club and pier shown here were destroyed by the slow-moving landslide. *(University of Washington Libraries)*

Mass wasting is a comprehensive term for any type of downslope movement of Earth materials. In its more restricted sense, mass wasting refers to a downslope movement of rock or soil as a more or less coherent mass. In this chapter, we consider landslides in the restricted sense. We will also discuss the related phenomena of earthflows and mudflows, rockfalls, and snow or debris avalanches. For the sake of convenience, we sometimes refer to all of these as **landslides**. We will also discuss *subsidence*, a type of ground failure characterized by nearly vertical deformation, or the downward sinking of Earth materials. Subsidence often produces circular surface pits but may produce linear or irregular patterns of failure.

10.2 Slope Processes and Types of Landslides

Slope Processes

Slopes are the most common landforms on Earth, and although most slopes appear stable and static, they are dynamic, evolving systems. Slopes are not generally uniform in their shape but are composed of segments that are straight or curved. Two different-looking slopes are shown in **Figure 10.4**. The first (Figure 10.4a) has a high cliff, or *free-face*, a straight, nearly vertical slope segment. This is a slope formed on hard granite rock in Yosemite National Park. Rock

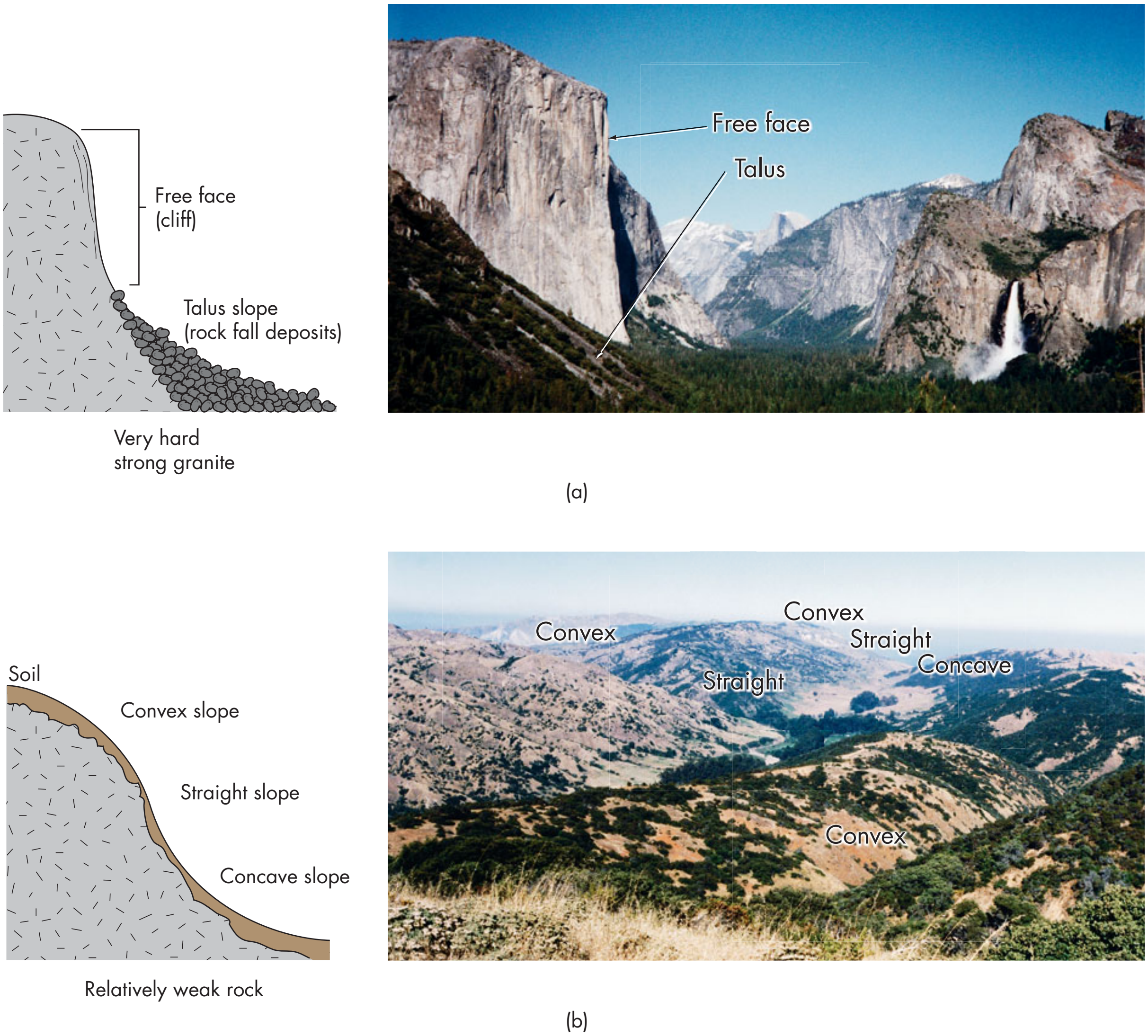


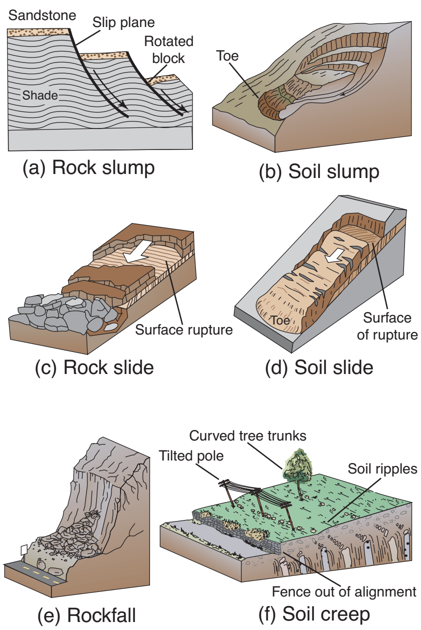
FIGURE 10.4 Slope segments (a) Slope on hard granite in Yosemite National Park with free-face (several thousand feet high) and talus slope. (b) Slopes on Santa Cruz Island, California, on relatively weak schist (red) and volcanic rocks (white), with convex, straight, and concave slope segments. *(Edward A. Keller)*

fragments that fall from the free-face may accumulate at the base of the slope to form a *talus* slope. The free-face and talus slopes are segments of the slope. Notice the surface cover of soil, missing on the free-face and talus slopes of Figure 10.4a. The hill slopes in Figure 10.4b are formed on rocks that are not nearly as strong as the granite in Yosemite. The slopes are gentler and lack a free-face. In this photo, there are three segments: an upper convex slope, a lower concave slope, and, separating the two, a straight slope. Thus, we see that slopes are usually composed of different slope segments. The five segment types above are sufficient to describe most slopes you will encounter in nature. Which slope segments are present on a particular slope depends on the rock type and the climate. Free-face development is more common on strong hard rocks or in arid environments where there is little vegetation. Convex and concave slopes are more common on softer rocks or with a more humid wet climate, where thick soil and vegetation are present. But there are many exceptions to these general rules, depending upon local conditions. For example, the gentle, convex, red-colored slopes in the lower part of Figure 10.4b have formed on weak, easily eroded metamorphic rock (schist) in a semiarid climate on Santa Cruz Island, California.

Material on most slopes is constantly moving down the slope at rates that vary from an imperceptible creep of soil and rock to thundering avalanches and rockfalls that move at tremendous velocities. These slope processes are one significant reason that valleys are much wider than the streams they contain.

Types of Landslides

Earth materials may fail and move or deform in several ways (**Figure 10.5**). Rotational slumps involve sliding along a curved slip plain, producing slump blocks (Figure 10.5a, b). Translational sliding is downslope movement of Earth materials along a planar slip plane, such as a bedding plane or frac-



Type of Movement	Materials	
	Rock	Soil
Landslides with variable water content and rate of movement	Rotational	
	Slump (a)	Slump (b)
	Translational	
	Rock slide (c)	Soil slide (slip) (d)
Falls	Rock fall (e)	Soil fall
Flows — Slow	Rock creep	Soil creep (f)
	Unconsolidated rock and soil (saturated)	
Rapid	Earth flow (g)	
	Debris flow / mud flow (h)	
Very rapid	Debris avalanche (i)	
Lateral spread	Rock (j)	Soil
Subsidence	Rock (k)	Soil
Complex	Combination of slides, slumps, and flows (l)	

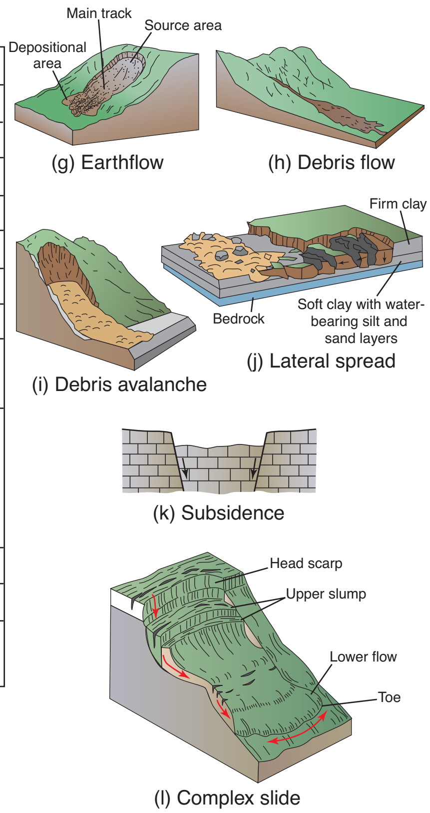


FIGURE 10.5 Types of landslides Classification of landslides, based on type of movement, materials, water content, and rate of movement. *(Modified after U.S. Geological Survey 2004. Fact Sheet 2004–3072)*

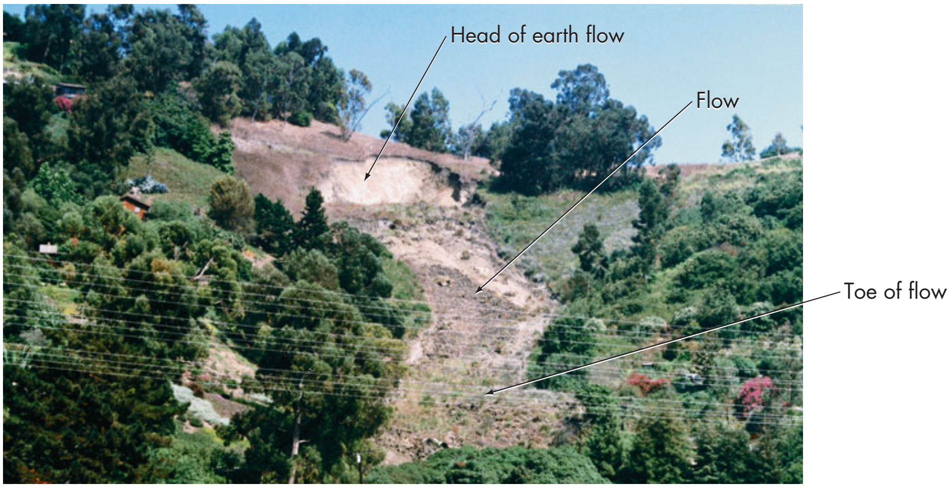


FIGURE 10.6 Earthflow This earthflow occurred on soft shale near Santa Barbara, California. *(Edward A. Keller)*

ture (Figure 10.5c, d). Rock fall is the free fall of Earth materials from a free-face of a cliff (Figure 10.5e). Flows are the downslope movement of unconsolidated (usually saturated) materials in which particles move about and mix within the mass. Very slow flowage of rock or soil is called *creep* (Figure 10.5f); rapid flowage may be an *earthflow*, a *mudflow*, or a *debris flow*. An earthflow (Figures 10.5g and **10.6**) often originates on a slope where soil partially liquefies and runs out. The source area becomes a bowl-shaped depression, and a depositional area spreads out at the toe of the slope, giving the event an hourglass shape. A debris flow or mudflow (Figure 10.5h) is a mixture of rock, soil, and organic matter that mixes with air and water to flow rapidly down slope. The upper part of the flow is often confined to a channel or valley but may spread out when it is no longer confined. A debris flow has less than 50 percent fines (sand, silt, and clay), whereas a mudflow has more than 50 percent fines by volume. A debris avalanche (Figure 10.5i) is a very rapid to extremely rapid debris flow. Large debris avalanches can cause catastrophic damage and loss of life. Lateral spreads (Figure 10.5j) are a type of landslide that often occurs on nearly flat slopes or very gentle slopes. The movement starts with liquefaction of silts, clays, or fine sands during earthquake shaking or other disturbance. The actual movement is lateral extension. If stronger coherent rock or soil is at the surface and is over a soil layer that liquefies, the stronger material may fracture, translate, rotate, or disintegrate and flow. Lateral spreads often start suddenly and then become larger in a slower, progressive manner.[4] Subsidence may occur on slopes or on flat ground and involves the sinking of a mass of Earth material below the level of the surrounding surface (Figure 10.5k).

Landslides are commonly complex combinations of sliding and flowage. As an example, Figures 10.5l and **10.7** show failures consisting of an upper *slump* that is transformed to a flow in the lower part of the slide. Such complex landslides may form when water-saturated Earth materials flow from the lower part of the slope, undermining the upper part and causing slumping of blocks of Earth materials.

Important variables in classifying downslope movements are the type of movement (i.e., slide, fall, flow, slump, complex movement), slope material type, amount of water present, and rate of movement. In general, the movement is considered rapid if it can be discerned with the naked eye; otherwise, it is classified as slow (Figure 10.5). Actual rates vary from a slow creep of a few millimeters or centimeters per year to very rapid, at 1.5 m (5 ft) per day, to extremely rapid, at 30 m (98 ft) or more per second.[5]

10.3 Slope Stability

Forces on Slopes

To determine the causes of landslides, we must examine slope stability, which can be expressed in terms of the forces that act on slopes. The stability of a slope expresses the relationship between *driving*

FIGURE 10.7 Complex landslide This 1995 slide, at La Conchita, California, which had an upper slump block and a lower flow, destroyed the three-story home in its path. *(Edward A. Keller)*

forces, which move Earth materials down a slope, and *resisting forces*, which oppose such movement. The most common driving force is the downslope component of the weight of the slope material, including anything superimposed on the slope, such as vegetation, fill material, or buildings. The most common resisting force is the strength, or the resistance to failure by sliding or flowing, of the slope material acting along potential slip planes. Potential *slip planes* are geologic surfaces exhibiting weakness in the slope material; for example, foliation planes in a slope composed of schist, bedding planes in sedimentary rocks, and fractures in all rock types are potential slip planes.

Slope stability is evaluated by computing a **factor of safety (FS)**, defined as the ratio of the resisting forces to the driving forces (see A Closer Look: Calculating a Factor of Safety for a Simple Landslide). If the factor of safety is greater than 1, the resisting forces exceed the driving forces, and the slope is considered stable. If the factory of safety is less than 1, the driving forces exceed the resisting forces, and a slope failure can be expected. Driving and resisting forces are not static: As local conditions change, these forces may change, increasing or decreasing the factor of safety.

Driving and resisting forces on slopes are determined by the interrelationships of the following variables:

- Type of Earth materials
- Slope angle and topography
- Climate
- Vegetation
- Water
- Time

The Role of Earth Material Type

The material composing a slope affects both the type and the frequency of downslope movement. Slides have two basic patterns of movement, rotational and translational. In **rotational slides**, or slumps, the sliding occurs along a curved slip surface (Figure 10.5a, b). Because the movement follows a curve, slump blocks (i.e., the blocks of Earth material that are undergoing slump) tend to produce topographic benches that can be rotated and tilted in the upslope direction like those in Figure 10.5b. Slumps are most common on soil slopes, but they also occur on some rock slopes, most often in weak rock, such as shale. **Translational slides** are planar; that is, they occur along inclined slip planes within a slope (Figure 10.5c, d) (see A Closer Look: Translation Slides Along Bedding Planes). Common translation slip planes in rock slopes include fractures in all rock types, bedding planes, weak clay layers, and foliation planes in metamorphic rocks. *Soil slips*, another type of trans-

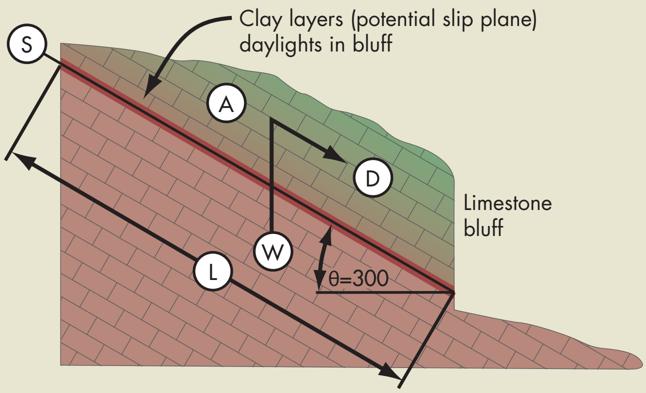
A Closer Look

Calculating a Factor of Safety for a Simple Landslide

Analysis of a slope for landslide risk involves determination of resisting and driving forces and the ratio of the two, which is the factor of safety (FS). This may be done for a simple translational slide, similar to a block of rock on an inclined plane (a slip plane). For example, consider the cross section shown in **Figure 10.A**, which shows a limestone bluff with a potential slip plane composed of clay that is found between bedding planes of the limestone and is inclined at an angle of 30° to a horizontal plane. The potential slip plane is said to "daylight" in the bluff (i.e., the ends of bedding planes are exposed on the slope [bluff], and, thus, the rocks above the slip plane are not well supported), presenting a potential landslide hazard. To determine the FS, we need to calculate the driving and resisting forces. A force (F) is a push or pull, defined quantitatively as the product of a mass (m) multiplied by an acceleration (a), written as F = ma. Using the equation, which is Newton's second law of motion, a force can be considered as a quantitative relationship between two objects, such as two masses of rock on a slope separated by a slip plane. With respect to slope processes, a force (e.g., the force of gravity) may be considered as a factor that causes an object at rest (i.e., rocks on a slope) to move downslope. The unit for force in the metric or SI system is the Newton, and, for the English system, the unit of force is the pound. For our problem, assume that the area above the slip plane in the cross section is 500 m^2. The unit weight (a force per unit volume) of the limestone is 1.6×10^4 N/m^3. Laboratory tests suggest that the shear strength of the clay (a force per unit area) along the slip plane is 9×10^4 N/m^2. Finally, from the cross section, the measured length of the slip plane is 50 m. With this information, we can calculate the FS as the ratio of resisting to driving forces by the equation:

$$\text{FS} = \frac{SLT}{W \text{ sine } \Theta}$$

We use what is known as the "unit thickness method" to analyze the resisting and driving forces for a slice (cross section in Figure 10.A) of the bluff, oriented perpendicular to the bluff, which is 1 m thick. The resisting forces are the product of *SLT*, where *S* is the shear strength of the clay, *L* is the length of the slip plane, and *T* is the unit thickness. The driving force is the downslope component of the weight of the slope material above the potential slip plane. This is *W* sine Θ, where *W* is equal to the product of the area above the slip plane *(A)*, the unit weight of the slope material, and *T* is the unit thickness. Then $W = (500\text{ m}^2)(1\text{ m})(1.6 \times 10^4\text{ N/m}^3) = 8 \times 10^6$ N. *W* is then multiplied by the sine of the angle of the slip plane, and the product (*W* sine Θ) is the downslope component of the weight of the slope materials above the potential slip plane (Figure 10.A). The sine of 30 degrees is 0.5. If the angle of the slip plane were 45 degrees, the sine would be 0.71. If the angle were 20 degrees, the sine would be 0.34. Thus, assuming that W is constant, with a steeper angle of the slip plane (at 45 degrees), the driving force increases, and, conversely, if



(A)=area of limestone above slip plane also is volume per unit width of slope (im)
(W)=weight of limestone above slip plane per unit width of slope (im)
(D)=downslope component of W is wsineθ is the driving force
(S)=shear strength of the clay is the main component of the resisting force
(L)=length of slip plane

FIGURE 10.A Factor of safety Components used to evaluate the factor of safety (FS) for a simple translation slide with a planar slip plane.

the angle is less (at 20 degrees), the driving forces are reduced.

The factor of safety is calculated as:

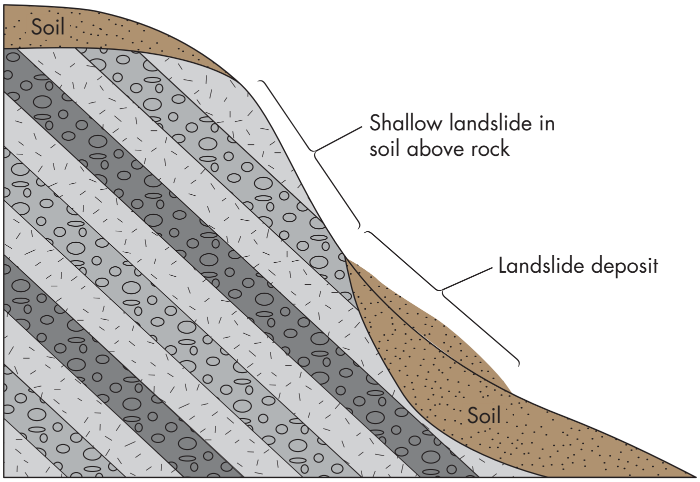
$$FS = \frac{SLT}{W \text{ sine } \Theta}$$

$$FS = \frac{(9 \times 10^4 \text{ N/m}^2)(50 \text{ m})(1 \text{ m})}{(500 \text{ m}^2)(1 \text{ m})(1.6 \times 10^4 \text{ N/m}^3)(0.5)}$$

$$FS = 1.13$$

The conclusion from our analysis, which resulted in a FS of 1.13, is not all that encouraging; generally, a FS less than 1.25 is considered conditionally stable. What could be done to increase the FS to at least 1.25? One possibility would be to remove some of the weight of the limestone above the potential slip plane. That is, reducing the driving force would increase the FS.

This example is a simple one for an inclined straight slip plane. Most slope stability problems are much more complex, involving variable rock strength along real and potential slip planes that may be curved.[6]



(a)

(b)

FIGURE 10.8 Multiple soil slips (a) Diagram of a shallow soil slip. (b) Shallow soil slips on steep slopes in southern California. The vegetation is low brush known as chaparral. *(Edward A. Keller)*

lational slide, can also occur in some areas. Soil slips are very shallow slides in soil over rock that occur parallel to the slope (**Figure 10.8**). For soil slips, the slip plane is usually above the bedrock but below the soil within a slope material known as *colluvium*, a mixture of weathered rock and other material (**Figure 10.9**, page 338).

Material type is a factor in falls, as well as in slides. If a resistant rock forms a very steep slope, weathering or erosion along fractures may cause a rockfall. Such failures on nearly vertical high slopes in hard granite present a continuous, chronic hazard in Yosemite National Park (**Figure 10.10**, page 339).

The type of materials composing a slope may greatly influence the type of slope failure that occurs. For example, on shale slopes or slopes on weak volcanic pyroclastic materials, failure commonly occurs as *creep*, the very slow downslope movement of soil or rock; *earthflows* or mudflows, the downslope flow of saturated Earth materials; slumps; or soil slips. Slopes formed in resistant rock, such as well-cemented sandstone, limestone, or granite, do not experience the same problems. Therefore, before developing on shale or other weak rock slopes, people must give careful consideration to the potential landslide hazard.

The Role of Slope and Topography

The hill slope angle, which is a measure of how steep a hill slope is, is usually called the *slope*. Slope greatly affects the

A Closer Look

Translation Slides Along Bedding Planes

Bedding planes are potential slip planes for landslides when they are inclined downslope and when they daylight (i.e., when they are exposed on the surface of a slope). A slope of a sea cliff with daylighting bedding planes in shale is diagrammatically shown in **Figure 10.B**. Several months later, in 2003, the slope failed, perhaps as a result of water being added to the top of the slope where grass was planted and watered. The landslide deposits cover part of the sandy beach (**Figure 10.C**), and a catastrophe was narrowly avoided as a beach party was happening a short distance away.

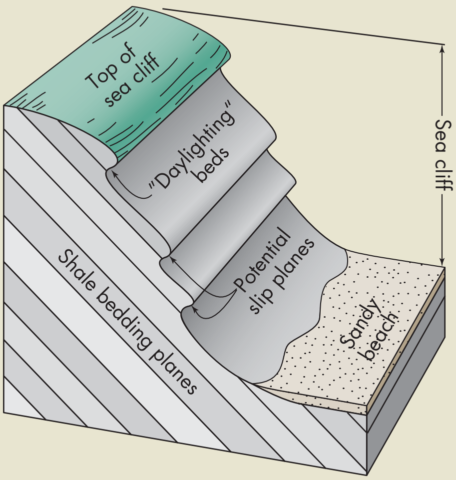


FIGURE 10.B Daylighting beds Bedding planes that intersect the surface of the land on a slope are said to "daylight." Such beds are potential slip planes.

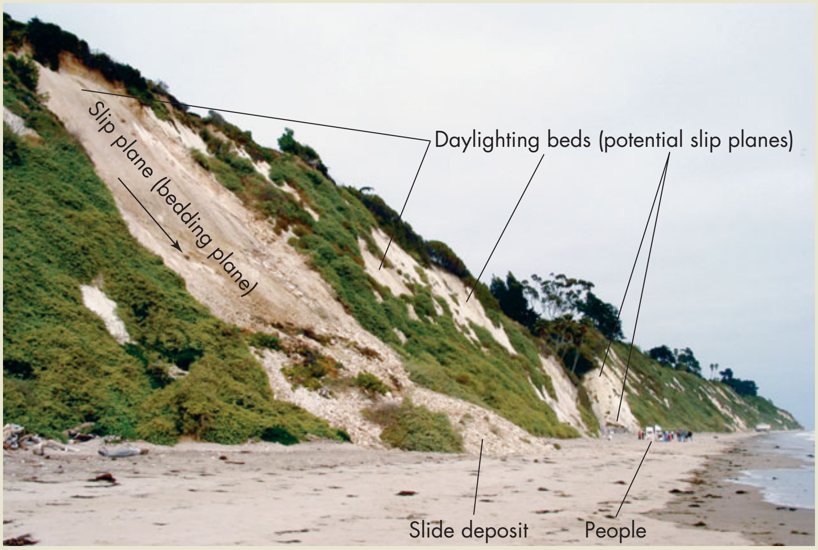


FIGURE 10.C Translation slide This slide occurred in late 2003. Failure was along a daylight bedding plane. Slide deposits cover part of the beach. *(Edward A. Keller)*

relative magnitude of driving forces on slopes. As the slope of a hillside or potential slip plane within a slope increases, say from 15 degrees to 45 degrees or steeper, the driving force also increases; therefore, landslides are more frequent on steep slopes. A study of landslides that occurred during two rainy seasons in California's San Francisco Bay area established that 75 to 85 percent of landslide activity is closely associated with urban areas on steep slopes.[7] Within the United States, the coastal mountains of California and Oregon, the Rocky Mountains, and the Appalachian Mountains have the greatest frequency of landslides. All of the types of downslope movement shown in Figure 10.5 occur on steep slopes in those locations.

Steep slopes are often associated with rockfalls and *debris avalanches*, which are the very rapid downslope movement of soil, rock, and organic debris. In southern California, shallow soil slips are common on steep saturated slopes. Once they move downslope, these soil slips are often transformed into earthflows or debris flows, which can be extremely hazardous (**Figure 10.11**, page 340). Earthflows can occur on moderate slopes, and creep can be observed on very gentle slopes.

Debris flows are the downslope flow of relatively coarse material; more than 50 percent of particles in

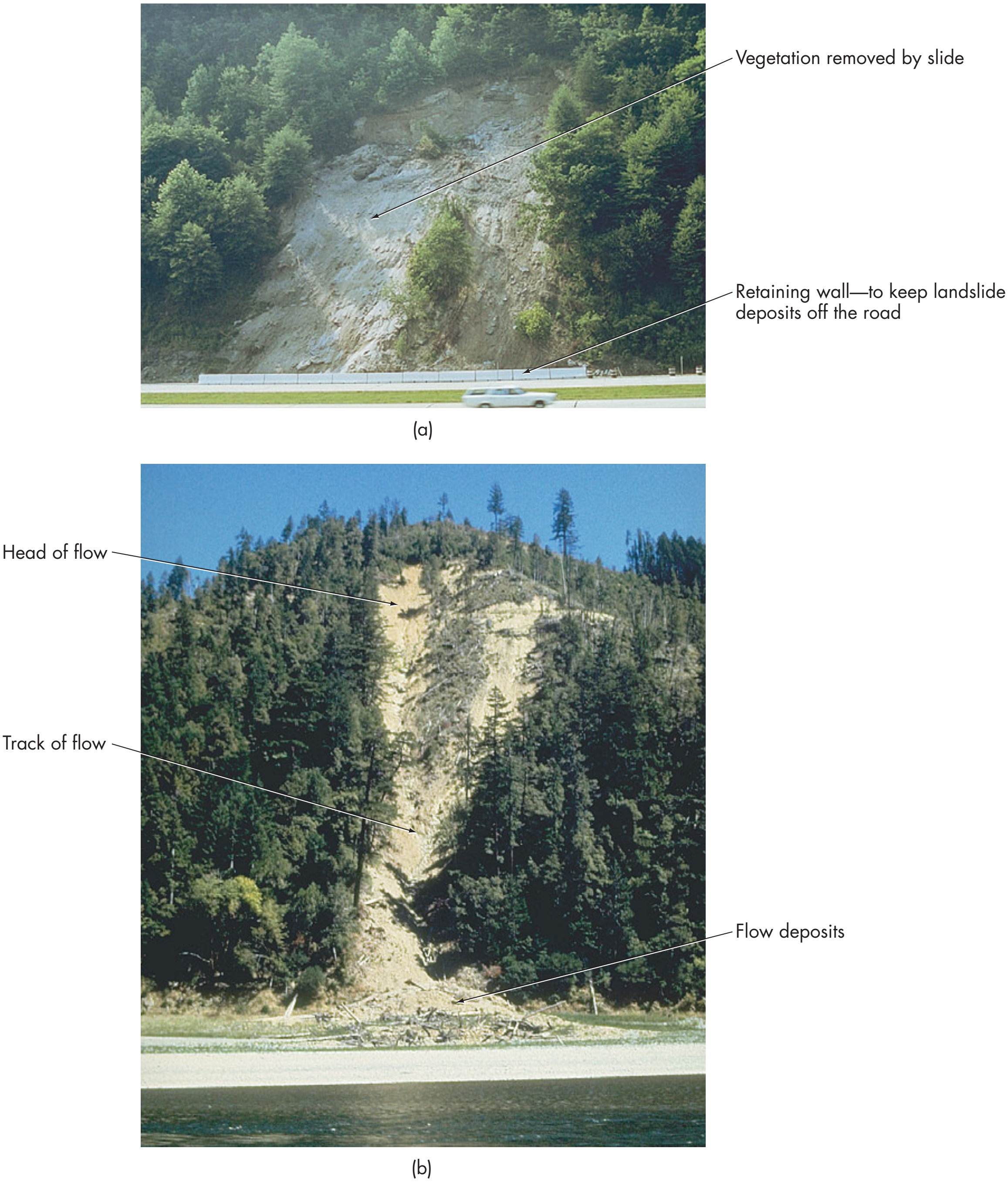


FIGURE 10.9 Shallow slides (a) Shallow soil slip, North Carolina. (b) Shallow debris flow, Klamath River, California. Note the long narrow track and debris on the bank of the river. The logging road near the bend of the failure may have helped destabilize the slope. *(Edward A. Keller)*

a debris flow are coarser than sand. Debris flows can move very slowly or rapidly, depending on conditions. Debris flows, debris avalanches, and mudflows vary in size: They can be relatively small to moderate events, confined to a single valley of slope with a few hundred cubic meters of debris to hundreds of thousands of cubic meters. However, they can also be huge events involving an entire flank of a mountain, measured in cubic kilometers of material. (Volcanic mudflows and debris flows are discussed in Chapter 8.)

(a)

(b)

FIGURE 10.10 Rockfall, Yosemite National Park, California (a) This rockfall occurred at 6:52 p.m. on July 10, 1996, at Happy Isles along the Merced River. The rockfall fell from near Glacier Point 665 m (2,180 ft) to the valley floor, reaching a speed or 110 m/s (250 mph). One person was killed, and more than 1,000 trees were blown down by the blast of air produced by compression of air in front and below the free-falling rock. The volume of rock was about 30,000 m^3. If the fall had occurred earlier, when numerous people were at the Happy Isles Visitors Center, many deaths could have resulted. *(Edwin L. Harp/USGS/U.S. Department of the Interior)* (b) A smaller rockfall on October 8, 2000, hit part of Camp Curry, destroying five tent cabins and injuring three people. *(Photo by Tom Trujillo/AP Photo)*

The Role of Climate

Climate can be defined as characteristic weather at a particular place or region over seasons, years, or decades. Climate is more than the average air temperature and amount of precipitation. Climate includes seasonal patterns of weather, such as winter rains along the West Coast of the United States, summer thunderstorm activity in the southwestern United States, and hurricane activity in the southeastern United States. The subject of climate and how it changes is discussed in detail in Chapter 18.

(a)

(b)

FIGURE 10.11 Shallow soil slips can kill (a) Shallow soil slips on steep southern California vegetated slopes. *(Edward A. Keller)* (b) A home in southern California destroyed by a debris flow that originated as a shallow soil slip. This 1969 event claimed two lives. *(Courtesy of John Shadle, Los Angeles Department of Building and Safety)*

The role of climate is important in our discussion of landslides because climate influences the amount and timing of water, in the form of rain and snow, that may infiltrate or erode a hill slope, as well as the type and abundance of vegetation that grows on a hill slope. Hill slopes in arid and semiarid climates tend to have sparse vegetation and soils with a lot of bare rock exposed. Slope segments, such as the free-face and talus slopes, tend to be more common because small differences in resistance of rock to weathering and erosion are emphasized. Common landslide activity in arid and semiarid regions includes rockfall, debris flows, and shallow soil slips.

The Role of Vegetation

In the more subhumid to humid regions of the world, vegetation is abundant, thick soil cover develops, and the slopes have many more convex and concave slope segments. Landslide activity includes deep complex landslides, earthflows, and soil creep. The role of vegetation in landslides and related phenomena is complex. Vegetation in an area is a function of several factors, including climate, soil type, topography, and fire history, each of which also influences what happens on slopes. Vegetation is a significant factor in slope stability for three reasons:

- Vegetation provides a cover that cushions the impact of rain falling on slopes, facilitating infiltration of water into the slope while retarding grain-by-grain erosion on the surface.
- Vegetation has root systems that tend to provide an apparent cohesion (like iron bars in concrete) to the slope materials, which increases resistance to landsliding.
- Vegetation adds weight to the slope.

In some cases, the presence of vegetation increases the probability of a landslide, especially for shallow soil slips on steep slopes. In southern California coastal areas, one type of soil slip occurs on steep-cut slopes covered with low vegetation called ice plant (**Figure 10.12**). During especially wet winter months, the shallow-rooted ice plants take up water, adding considerable weight to steep slopes—each leaf stores water and looks like a small canteen—thereby increasing the driving forces. The plants also cause an increase in the infiltration of water into the slope, which decreases the resisting forces. When failure occurs, the plants and several centimeters of roots and soil slide to the base of the slope.

FIGURE 10.12 Ice plants on slopes are often unstable Shallow soil slips on steep slopes covered with shallow-rooted ice plants near Santa Barbara, California: (a) an embankment on a road; (b) a home site. The plastic sheet is an attempt to reduce infiltration of rainwater. *(Edward A. Keller)*

Soil slips on natural steep slopes are a serious problem in southern California. Chaparral, the dense shrubs or brush shown in Figure 10.8, facilitates an increase in water infiltrating into the slope, lowering the factor of safety.[8]

The Role of Water

Water is almost always directly or indirectly involved with landslides, so its role is particularly important.[9] When studying a landslide, we first examine what the water on or in the slope is doing. There are three basic ways in which water on or in a slope can affect stability: (1) Landslides, such as shallow soil slips, can develop during rainstorms when slopes become saturated; (2) landslides, such as slumps or translational slides, can develop months or even years after infiltration of water deep into the slope; and (3) water can erode the base or toe of a slope, thereby decreasing slope stability.

Water's ability to erode affects the stability of slopes. Stream or wave erosion on a slope may remove material and create a steeper slope, thus reducing the factor of safety (**Figure 10.13**). This problem is particularly critical if the base of the slope is an old, inactive landslide that is likely to move again if stability is reduced (**Figure 10.14**). Therefore, it is important to recognize old landslides along potential road cuts and other excavations before construction in order to isolate and correct potential problems.

Another way that water can cause landslides is by contributing to spontaneous liquefaction of clay-rich sediment, or *quick clay*. When disturbed, some clays temporarily lose their shear strength, behave as a liquid, and flow. The shaking of clay below Anchorage, Alaska, during the 1964 earthquake produced this effect and was extremely destructive. In Quebec, Canada, several large slides associated with quick clays have destroyed numerous homes and killed about 70 people. The slides occurred on river valley slopes when initially solid material was converted into a liquid mud as the sliding movement began.[10] These slides are especially interesting because the liquefaction of clays occurs without earthquake shaking. The slides are often initiated by river erosion at the toe of the slope and, although they start in a small area, they may develop into large events. Since they often involve the reactivation of an older slide, future problems may be avoided by restricting development in these areas.

The Role of Time

The forces on slopes often change with time. For example, both driving and resisting forces may change seasonally as the moisture content or water table position alters. Much of the chemical weathering of rocks, which slowly reduces their strength, is caused by the chemical action of water in contact with soil and rock near Earth's surface. Water

(a)

(b)

FIGURE 10.13 Water eroding the toe of a slope causes instability (a) Stream-bank erosion caused this failure, which damaged a road, San Gabriel Mountains, California. *(Edward A. Keller)* (b) Beachfront home being threatened by a landslide, Cove Beach, Oregon. *(Gary Braasch)*

(a)

(b)

FIGURE 10.14 Reactivation of a slide (a) Aerial view of a landslide along the Santa Barbara coastal area. The arrow points to the location of the slide. (b) Close-up of the slide, which destroyed two homes. The slide is a reactivation of an older failure. *(Courtesy of Don Weaver)*

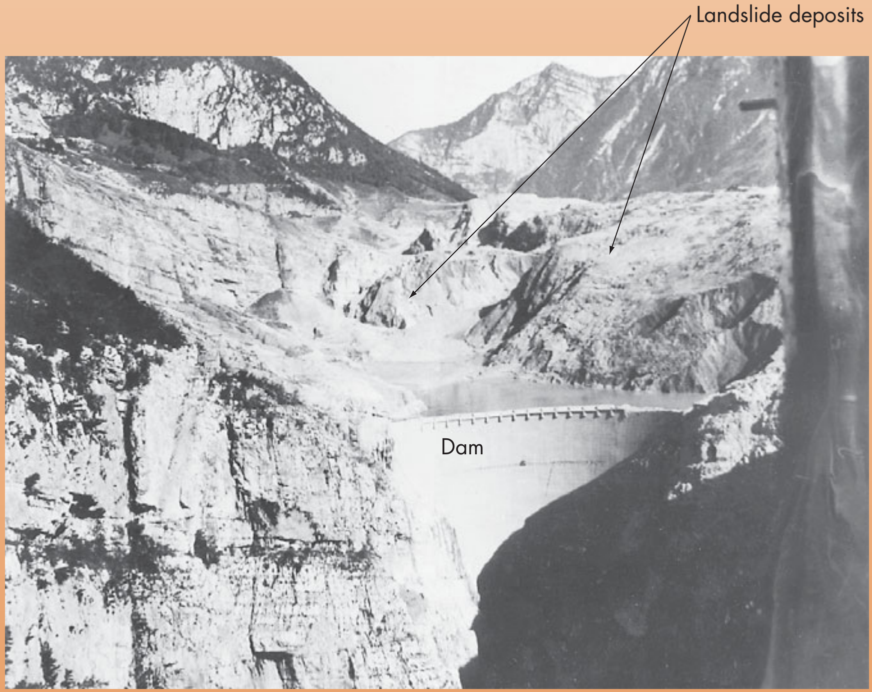
(H_2O) is often acidic because it reacts with carbon dioxide (CO_2) in the atmosphere and soil to produce weak carbonic acid (H_2CO_3). This chemical weathering is especially significant in areas with limestone, which is susceptible to weathering and decomposition by carbonic acid. Changes due to weathering are greater in especially wet years, as reflected by the increased frequency of landslides during or after wet years. In other slopes, there may be a continuous reduction in resisting forces over time, perhaps due either to weathering, which reduces the cohesion in slope materials, or to a regular increase in pore water pressure in the slope from natural or artificial conditions. A slope that is becoming less stable with time may have an increasing rate of creep until failure occurs. The case history of the Vaiont Dam illustrates this concept (see Case History: Vaiont Dam).

Case History

Vaiont Dam

(a)

The world's worst dam disaster occurred on October 9, 1963, when approximately 2,600 lives were lost at the Vaiont Dam in Italy (**Figure 10.D**). The disaster involved the world's highest thin-arch dam, yet, strangely, no damage was sustained by the main shell of the dam or the abutments.[11] The tragedy was caused by a huge landslide in which more than 238 million m^3 (0.06 mi^3) of rock and other debris moved at speeds of about 95 km per hour (59 mi per hour) down the north face of the mountain above the reservoir. Slide material completely filled the reservoir for 1.8 km (1.1 mi) along the axis of the valley to heights of nearly 152 m (500 ft) above the reservoir level. The rapid movement created a tremendous updraft of air and propelled rocks and water up the north side of the valley, higher than 250 m



(b)

FIGURE 10.D Sketch map of the Vaiont Reservoir (a) A diagram showing the 1963 landslide that displaced water that overtopped the dam and caused severe flooding and destruction over large areas downstream. A–A′ and B–B′ are the cross sections shown in Figure 10.E. *(After Kiersch, G. A.* Civil Engineering *34:32–39)* (b) Photograph of the Vaoint Dam after the landslide. Notice that the concrete dam is still intact but the reservoir above the dam is nearly completely filled with landslide deposits. *(ANSA)*

(820 ft) above the reservoir level. The slide and its accompanying blasts of air, water, and rock produced strong earthquakes recorded many kilometers away. It blew the roof off one man's house well over 250 m (820 ft) above the reservoir and pelted the man with rocks and debris. The filling of the reservoir produced waves of water more than 90 m (295 ft) high that swept over the abutments of the dam. The waves were still more than 70 m (230 ft) high more than 1.5 km (0.9 mi) downstream; in fact, everything for many kilometers downstream was completely destroyed. The entire event—slide and flood—was over in less than 7 minutes.

The landslide followed a 3-year period of monitoring the rate of creep on the slope, which varied from less than 1 cm to as many as 30 cm (12 in.) per week, until September 1963, when it increased to 25 cm (10 in.) per day. Finally, on the day before the slide, it was about 100 cm (39 in.) per day. Although engineers expected a landslide, they did not realize until the day before the slide that a large area was moving as a uniform, unstable mass. Interestingly, animals grazing on the slope had sensed danger and moved away on October 1, over a week before the landslide.

The slide was caused by a combination of factors. First, adverse geologic conditions—including weak rocks and limestone with open fractures, sinkholes, and weak clay layers that were inclined toward the reservoir—produced unstable blocks (**Figure 10.E**). Second, very steep topography created a strong driving force. Third, water pressure was increased in the valley rocks because of the water in the reservoir. The rate of creep before the slide increased as the groundwater level rose in response to higher reservoir levels. Fourth, heavy rains from late September until the day of the disaster further increased the weight of the slope materials, raised the water pressure in the rocks, and produced runoff that continued to fill the reservoir even after engineers tried to lower the reservoir level.

Officials concluded that the disaster was caused by an increase in the driving forces, accompanied by a great decrease in the resisting forces, as rising groundwater in the slope increased along zones of weakness in the rock.[11]

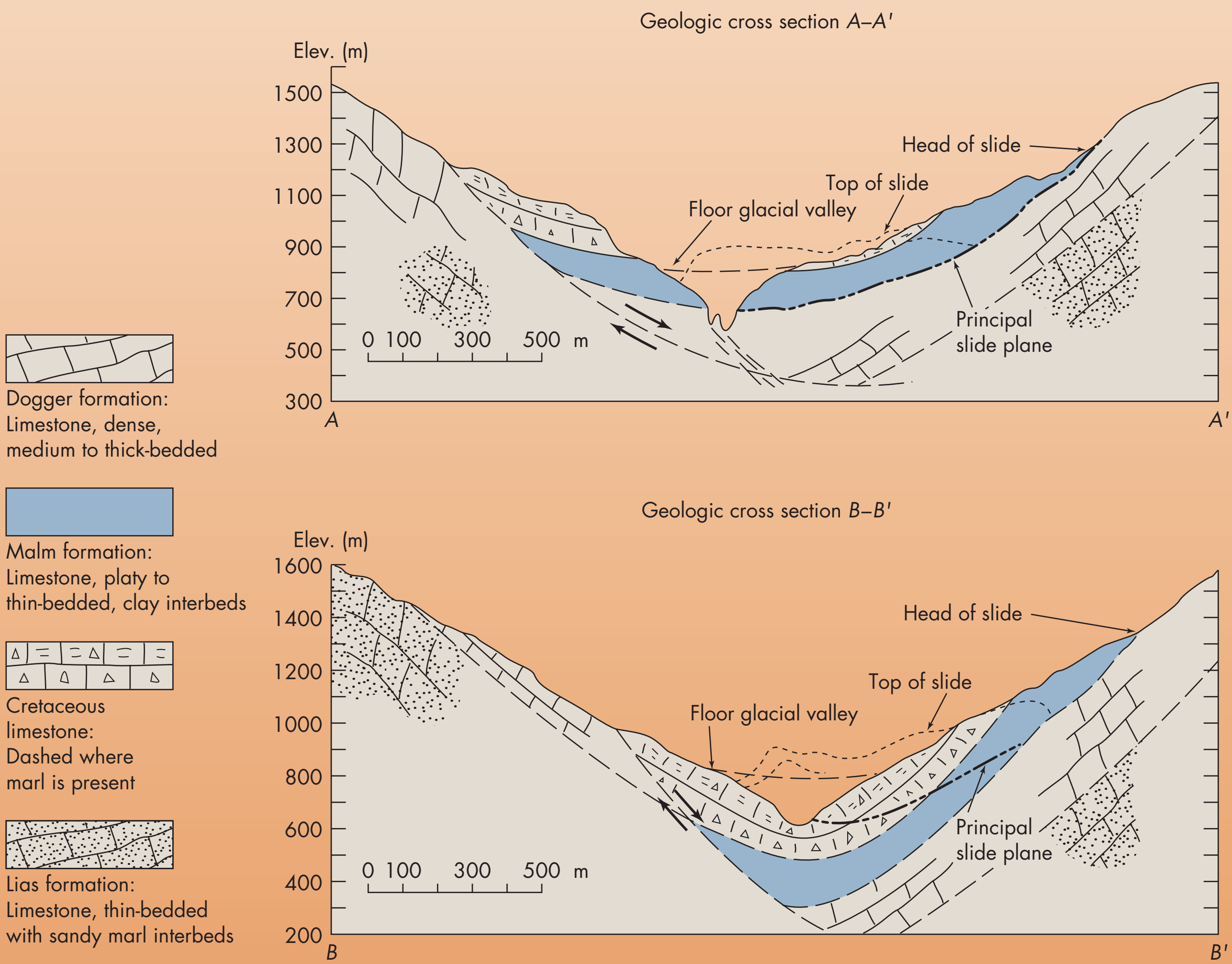


FIGURE 10.E Generalized geologic cross sections These cross sections show the slide area of the Vaiont River Valley. The locations of the sections are shown in Figure 10.D. *(After Kiersch, G. A.* Civil Engineering *34:32–39)*

10.4 Human Use and Landslides

The effect of human use on the magnitude and frequency of landslides varies from nearly insignificant to very significant. In cases in which our activities have little to do with the magnitude and frequency of landslides, we need to learn all we can about where, when, and why they occur to avoid developing in hazardous areas and to minimize damage. In cases in which human use has increased the number and severity of landslides, we need to learn how to recognize, control, and minimize their occurrence wherever possible.

Many landslides have been caused by interactions of adverse geologic conditions, excess moisture, and artificial changes in the landscape and slope material. The Vaiont Dam and Reservoir slide of 1963 in Italy is a classic example (see Case History: Vaiont Dam). Other examples include landslides associated with timber harvesting, as well as numerous slides in urban areas.

Timber Harvesting

The possible cause-and-effect relationship between timber harvesting and erosion in northern California, Oregon, and Washington is a controversial topic. There is evidence to support the hypothesis that landslides, especially shallow soil slips, debris avalanches, and more deeply seated earthflows, are responsible for much of the erosion in these areas. In fact, one study in the western Cascade Range of Oregon concluded that shallow slides are the dominant erosion process in the area. Timber-harvesting activities, such as clear-cutting and road building over approximately a 20-year observation period on geologically stable land, did not greatly increase landslide-related erosion. During that same time period, however, logging on weak, unstable slopes did increase landslide erosion by several times compared with landslide erosion on forested land.[12]

The construction of roads in areas to be logged is an especially serious problem because roads may interrupt surface drainage, alter subsurface movement of water, and adversely change the distribution of mass on a slope by cut-and-fill, or grading, operations.[12] As we learn more about erosional processes in forested areas, we are developing improved management procedures to minimize the adverse effects of timber harvesting. Nevertheless, we are not yet out of the woods with respect to landslide erosion problems associated with timber harvesting.

Urbanization

Human activities are most likely to cause landslides in urban areas where there are high densities of people and supporting structures, such as roads, homes, and industries. Examples from Rio de Janeiro, Brazil, and Los Angeles, California, illustrate the situation.

Rio de Janeiro, with a population of more than 6 million people, may have more slope-stability problems than any other city its size.[13] The city is noted for the beautiful granite peaks that spectacularly frame the urban area (**Figure 10.15**). Combinations of steep slopes and fractured rock covered with thin soil contribute to the problem. In the past, many such slopes were logged for lumber and fuel and to clear space for agriculture. Landslides associated with heavy rainfall followed the logging activity. More recently, lack of room on flat ground has led to increased urban development on slopes. Vegetation cover has been removed, and roads leading to development sites at progressively higher areas are being built. Excavations have cut the base of many slopes and severed the soil mantle at critical points. In addition, placing slope fill material below excavation areas has increased the load on slopes already unstable before the fill. Because this area periodically experiences tremendous rainstorms, it is apparent that Rio de Janeiro has a serious problem.

In February 1988, an intense rainstorm dumped more than 12 cm (4.7 in.) of rain on Rio de Janeiro in 4 hours. The storm caused flooding and mudslides that killed about 90 people, leaving about 3,000 people homeless. Restoration costs exceeded $100 million. Many of the landslides were initiated on steep slopes where housing was precarious and control of stormwater runoff nonexistent. It was in these hill-hugging shantytown areas that most of the deaths from mudslides occurred. Intense rainfall, as much as 15 cm (6 in) over 24 hours, in January 2011 caused wide spread flash flooding, debris flows, debris avalanches, and shallow landslides about 60 km northeast of Rio de Janeiro. Over 600 people were killed and thousands become homeless. The 2011 event is the worst extreme rainfall with floods/landslides in Brazil history.

Los Angeles in particular and southern California in general have experienced a remarkable frequency

FIGURE 10.15 Landslides are common in the Rio de Janeiro area Panoramic view of Rio de Janeiro, Brazil, showing the steep (sugarloaf) hills. The combination of steep slopes, fractured rock, shallow soils, and intense precipitation contributes to the landslide problem, as do human activities, such as urbanization, logging, and agriculture. Virtually all of the bare rock slopes were at one time vegetated, and that vegetation has been removed by landsliding and other erosional processes. *(Jupiter Images)* Landslides north of Rio (inset photo) that occurred in mid January 2011. *(Felipe Dana/AP Photo)*

of landslides associated with hillside development. Landslides in southern California result from complex physical conditions, in part because of the great local variation in topography, rock and soil types, climate, and vegetation. Interactions between the natural environment and human activity are complex and notoriously unpredictable. For this reason, the area has the sometimes dubious honor of showing the ever-increasing value of the study of urban geology. [14] Los Angeles has led the nation in developing building codes concerning grading for development.

In southern California, the grading process, in which benches (referred to as *pads*) are cut into slopes for home sites, has been responsible for many landslides. It took natural processes many thousands, if not millions, of years to produce valleys, ridges, and hills. In this century, we have developed the machines to grade them. F. B. Leighton writes: "With modern engineering and grading practices and appropriate financial incentive, no hillside appears too rugged for future development."[14] No Earth material can withstand the serious assault of modern technology. Thus, human activity is a geologic agent capable of carving the landscape as do glaciers and rivers, but at a tremendously faster pace. Almost overnight, we can convert steep hills into a series of flat lots and roads, and such conversions have led to numerous artificially induced landslides. As shown in **Figure 10.16**, oversteepened slopes in conjunction with increased water from sprinkled lawns or septic systems, as well as the additional weight of fill material and a house, make formerly stable slopes unstable. As a rule, any project that steepens or saturates a slope increases its height or places an extra load on it that may cause a landslide.[14]

Landslides on both private and public land in Hamilton County, Ohio, have been a serious problem. The slides occur in glacial deposits, composed mostly of clay, lake-bed sediments, and unstratified material called *till*, as well as colluvium and soil formed on shale. The average cost of damage exceeds $5 million per year. Major landslides in Cincinnati, Ohio, have damaged highways and several private structures.[19]

Modification of sensitive slopes associated with urbanization in Allegheny County, Pennsylvania, is estimated to be responsible for 90 percent of the landslides in the area. An average of $2 million in damages results each year from these landslides. Most of the landslides are slow moving, but one rockfall in an adjacent county crushed a bus and killed 22 passengers. Most of the landslides in Allegheny County are caused by construction activity that loads the top of a slope, cuts into a sensitive location, such as the toe of a slope, or alters water conditions on or beneath the surface of a slope.[15]

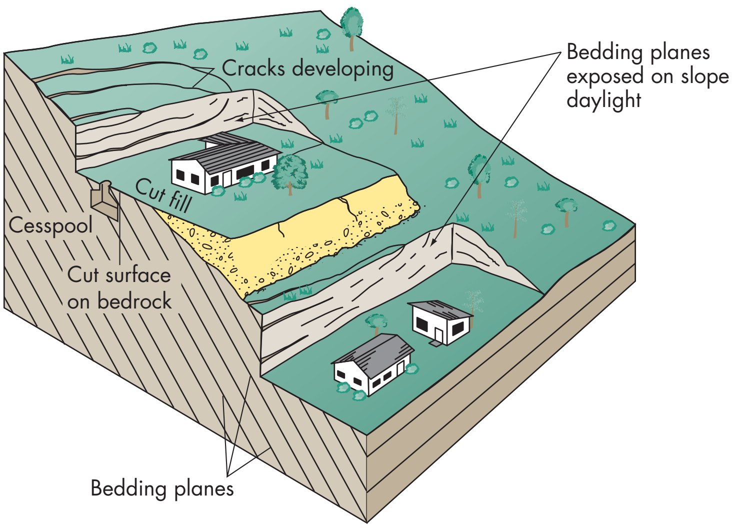


FIGURE 10.16 Urbanization and landslide potential Development of artificial translational landslides. Stable slopes may be made unstable by a variety of alterations, including removing support from the bedding plane surfaces, adding water to the slope, steepening the slope, and adding fill on the slope. The cracks shown in the upper part of the diagram are an early sign that a landslide is likely to occur soon. *(Reprinted, with permission, from Leighton F. B. 1966. "Landslides and urban development." In* Engineering Geology in Southern California. *Los Angeles: Los Angeles Section of the Association of Engineering Geology)*

10.5 Minimizing the Landslide Hazard

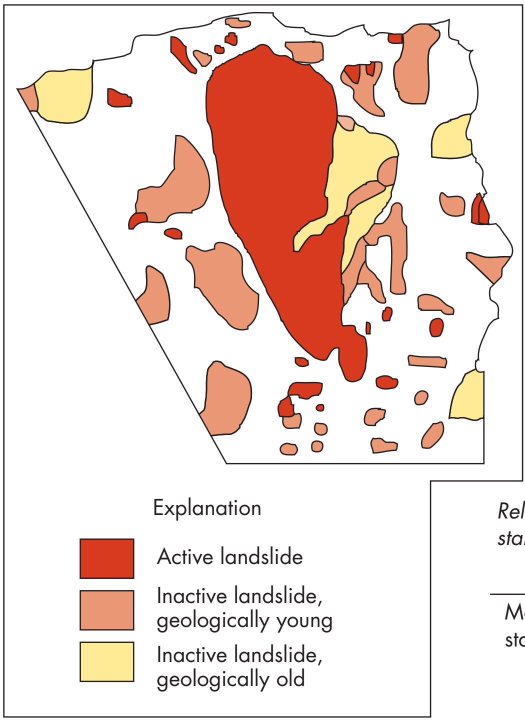
Minimizing the landslide hazard requires identifying areas in which landslides are likely to occur, designing slopes or engineering structures to prevent landslides, warning people in danger areas of impending slides, and controlling slides after they have started moving. The most preferable and least expensive option to minimize the landslide hazard is to avoid development on sites where landslides are occurring or are likely to occur.

Identifying Potential Landslides

Identifying areas with a high potential for landslides is the first step in developing a plan to avoid landslide hazards. Slide tendency can be recognized by examining both geologic conditions in the field and aerial photographs to identify previous slides. This information can then be used to evaluate the risk and produce slope stability maps.

Once a landslide hazard is identified, it must be evaluated. A landslide inventory, which may be a reconnaissance map showing areas that have apparently experienced slope failure, should be prepared. This inventory may be done by aerial photographic interpretation, followed by an onsite check. At a more detailed level, the landslide inventory may be a map that shows definite landslide deposits in terms of their relative activity. Figure 10.17a shows an example of such a map for part of Santa Clara County, California. Information concerning past landslide activity may then be combined with land-use considerations to develop a slope stability or landslide hazard map with recommended land uses, as shown in Figure 10.17b. The latter map is of most use to planners, whereas the former supplies useful information for engineering geologists. These maps do not take the place of detailed fieldwork to evaluate a specific site but serve only as a general guideline for land-use planning and more detailed geologic evaluation. Determining the landslide risk and making landslide risk maps is more complicated, since it involves the probability of occurrence and assessment of potential losses.[16]

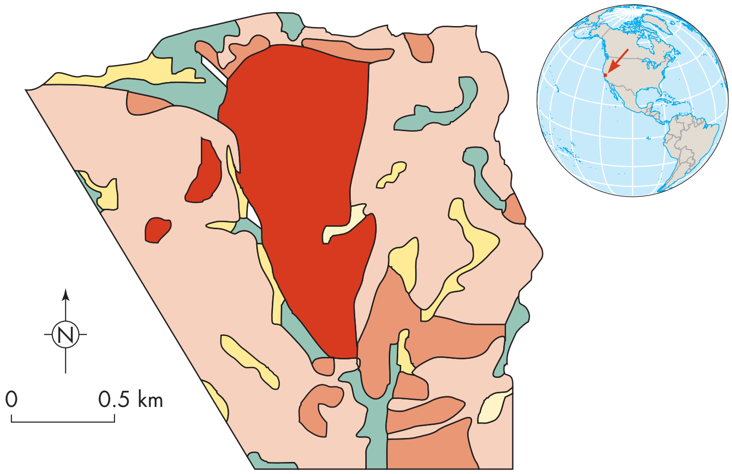
Grading codes to minimize the landslide hazard have been in effect in the Los Angeles area since 1963. These codes were instituted in the aftermath of the landsliding in the 1950s and 1960s that resulted in great losses of life and property. Since the grading codes have been in effect and detailed engineering geology studies have been required, the percentage of hillside homes damaged by landslides and floods has been greatly reduced. Although initial building costs are greater because of the strict codes, they are more than balanced by the reduction of losses in subsequent wet years. Landslide disasters during extremely wet years will continue to plague us; however, the application of geologic and engineering information before hillside development can help minimize the hazard.



(a)

Yes*
The land use would normally be expected to be permitted, provided the geologic data and (or) engineering solutions are favorable. However, there will be instances where the use will not be appropriate.

No*
The land use would normally be expected to not be permitted. However, there will be circumstances where geologic data and (or) engineering solutions will permit the use.



Relative stability	*Map area*	*Geologic conditions*	*Recommended land use* Houses	Roads Public	Roads Private
Most stable		Flat or gentle slopes; subject to local shallow sliding, soil creep, and settlement	Yes	Yes	Yes
		Gentle to moderately steep slopes in older stabilized landslide debris; subject to settlement, soil creep, and shallow and deep landsliding	Yes*	Yes*	Yes*
		Steep to very steep slopes; subject to mass-wasting by soil creep, slumping, and rock fall	Yes*	Yes*	Yes*
		Gentle to very steep slopes in unstable material subject to sliding, slumping, and soil creep	No*	No*	No*
		Moving, shallow (< 3 m) landslide	No*	No*	No*
Least stable		Moving, deep landslide, subject to rapid failure	No	No	No

(b)

FIGURE 10.17 Landslide hazard map (a) Landslide inventory map and (b) landslide risk and land-use map for part of Santa Clara County, California. *(After U.S. Geological Survey. 1982.* Goals and Tasks of the Landslide Part of a Ground-Failure Hazards Reduction Program. *U.S. Geological Survey Circular 880)*

Preventing Landslides

Preventing large, natural landslides is difficult, but common sense and good engineering practices can help to minimize the hazard. For example, loading the top of slopes, cutting into sensitive slopes, placing fills on slopes, or changing water conditions on slopes should be avoided or done with caution.[15] Common engineering techniques for landslide prevention include provisions for surface and subsurface drainage, removal of unstable slope materials, construction of retaining walls or other supporting structures, or some combination of these.[5]

Drainage Control. Surface and subsurface drainage control are usually effective in stabilizing a slope. The objective is to divert water to keep it from running across or infiltrating into the slope. Surface water may be diverted around the slope by a series of surface drains. This practice is common for road cuts (**Figure 10.18a**). The amount of water infiltrating a slope may also be controlled by covering the slope with an impermeable layer, such as soil-cement, asphalt, or even plastic (Figure 10.18b). Groundwater may be inhibited from entering a slope by constructing subsurface drains. A drainpipe

FIGURE 10.18 Two ways to increase slope stability (a) Drains on a road cut to remove surface water from the cut before it infiltrates the slope. (b) Covering a slope with a soil-cement in Greece to reduce infiltration of water and provide strength. *(Edward A. Keller)*

with holes along its length is surrounded with permeable gravel or crushed rock and is positioned underground so as to intercept and divert groundwater away from a potentially unstable slope.[5]

Grading. Although grading of slopes for development has increased the landslide hazard in many areas, carefully planned grading can be used to increase slope stability. In a single cut-and-fill operation, material from the upper part of a slope is removed and placed near the base. The overall gradient is thus reduced, and material is removed from an area where it contributes to the driving forces and is placed at the toe of the slope, where it increases the resisting forces. However, this method is not practical on very steep, high slopes. As an alternative, the slope may be cut into a series of benches or steps. The benches are designed with surface drains to divert runoff. The benches reduce the overall slope of the land and are good collection sites for falling rock and small slides (**Figure 10.19**).[5]

Slope Supports. Retaining walls constructed from concrete, stone-filled wire baskets, or piles (i.e., long concrete, steel, or wooden beams driven into the ground) are designed to provide support at the base of a slope (**Figure 10.20**). They should be anchored well below the base of the slope, backfilled with permeable gravel or crushed rock (**Figure 10.21**) and provided with drain holes to reduce the chances of water pressure building up in the slope (Figure 10.21). The evolution of a retaining wall is shown in **Figure 10.22** (page 351). A shallow landslide along a road causes a problem (Figure 10.22a). The wall is shown during construction in 1999 in Figure 10.22b.

FIGURE 10.19 Benching The upper-right quadrant shows a slope along the Pacific Ocean created to reduce the overall steepness of the slope and provide for better drainage. *(Edward A. Keller)*

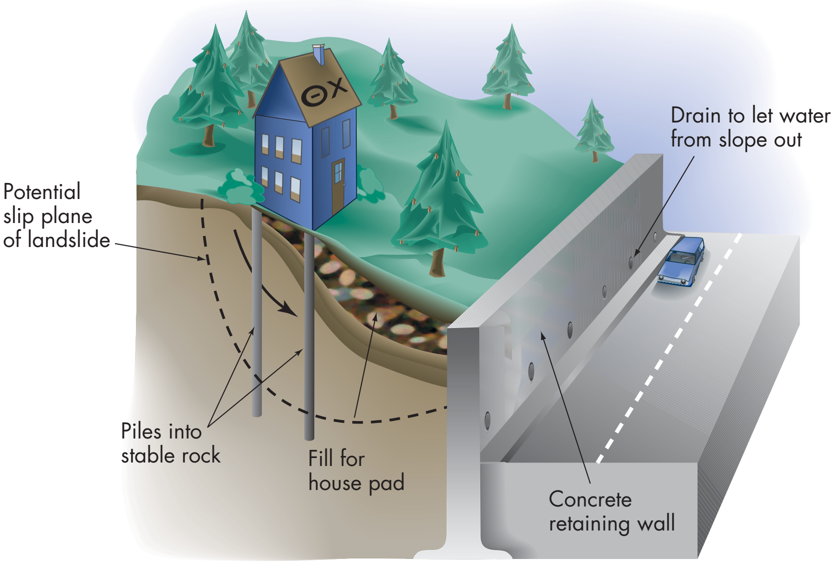


FIGURE 10.20 How to support a slope Some types of slope support: retaining walls, piles, and drains.

FIGURE 10.21 Retaining wall This retaining wall, made of concrete cribbing with backfill, helps stabilize a road cut. *(Edward A. Keller)*

The finished wall in 2001 now stabilizes the slope (Figure 10.22c).

Preventing landslides can be expensive, but the rewards can be well worth the effort. It has been estimated that the benefit-to-cost ratio for landslide prevention ranges from approximately 10 to 2,000. That is, for every dollar spent on landslide prevention, the savings will vary from $10 to $2,000.[17] The cost of *not* preventing a slide is illustrated by the massive landslide in Utah known as the Thistle slide. In April 1983, this slide moved across a canyon, creating a natural dam about 60 m (197 ft) high and flooding the community of Thistle, the Denver–Rio Grande Railroad and its switchyard, and a major U.S. highway (**Figure 10.23**, page 352).[17] The landslide and resultant flooding caused approximately $200 million in damages.

The Thistle slide involved a reactivation of an older slide that had been known for many years to be occasionally active in response to high precipitation. Therefore, it could have been recognized that the extremely high amounts of precipitation in 1983 would cause a problem. In fact, a review of the landslide history suggests that the Thistle landslide was recognizable, predictable, and preventable! Analysis of the pertinent data suggests that emplacement of subsurface drains and control of surface runoff would have lowered the water table in the slide mass enough to have prevented failure. The cost of preventing the landslide was estimated to be between $300,000 and $500,000, a small amount compared with the damages caused by the slide.[17] Because the benefit-to-cost ratio in landslide prevention is so favorable, it seems prudent to evaluate active and potentially active landslides in areas where considerable damage may be expected and possibly prevented.

(a)

(b)

FIGURE 10.22 Steps in making a retaining wall
(a) Shallow slide in the early 1990s. (b) Retaining wall being constructed in 1999 to correct the problem. (c) Finished wall in 2001. *(Edward A. Keller)*

(c)

Warning of Impending Landslides

Landslide warning systems do not prevent landslides, but they can provide time to evacuate people and their possessions and to stop trains or reroute traffic. Surveillance provides the simplest type of warning. Hazardous areas can be visually inspected for apparent changes, and small rockfalls on roads and other areas can be noted for quick removal. Human monitoring of the hazard has the advantages of reliability and flexibility but becomes disadvantageous during adverse weather and in hazardous locations.[18] Other warning methods include electrical systems, tilt meters, and geophones that pick up vibrations from moving rocks. Shallow wells can be monitored to signal when slopes contain a dangerous amount of water. These methods are part of real-time monitoring (**Figure 10.24**, page 353).[19] In some regions, monitoring rainfall is useful for detecting when a threshold precipitation has been exceeded and shallow soil slips become more probable.

Correcting Landslides

After a slide has begun, the best way to stop it is to attack the process that started the slide. In most cases, the cause of the slide is an increase in water pressure, and, in such cases, an effective drainage program must be initiated. This may include installing surface drains at the head of the slide to keep additional surface water from infiltrating and subsurface drainpipes or wells to remove water and lower the water pressure. Draining tends to increase the resisting force of the slope material, thereby stabilizing the slope.[9]

10.6 Snow Avalanches

A **snow avalanche** is a rapid downslope movement of snow and ice, sometimes with the addition of rock, soil, and trees. Thousands of avalanches occur every year in the western United States. As more people venture into avalanche-prone areas and more development occurs in these areas, the loss of life and property due to avalanches increases. The most damaging avalanches occur when a large slab of snow and ice, weighing millions of tons, fails due

FIGURE 10.23 Landslide blocks a canyon Thistle landslide, Utah. This landslide, which occurred in 1983, involved the reactivation of an older slide. The landslide blocked the canyon, creating a natural dam, flooding the community of Thistle, the Denver–Rio Grande Railroad, and a major U.S. highway. *(Michael Collier)*

to the overloading of a slope with fresh snow or to development of zones of weakness within the snowpack. These slabs move rapidly downslope at velocities of up to 100 km per hour (62 mi per hour). Avalanches tend to move down tracks, called *chutes*, that have previously produced avalanches (**Figure 10.25**, page 354). As a result, maps delineating the hazard may be developed. Avoiding hazardous areas is obviously the preferred and least expensive adjustment to avalanches. Other adjustments include clearing excess snow with carefully placed explosives, constructing buildings and structures to divert or retard avalanches, or planting trees in avalanche-prone areas to better anchor the snow on slopes.

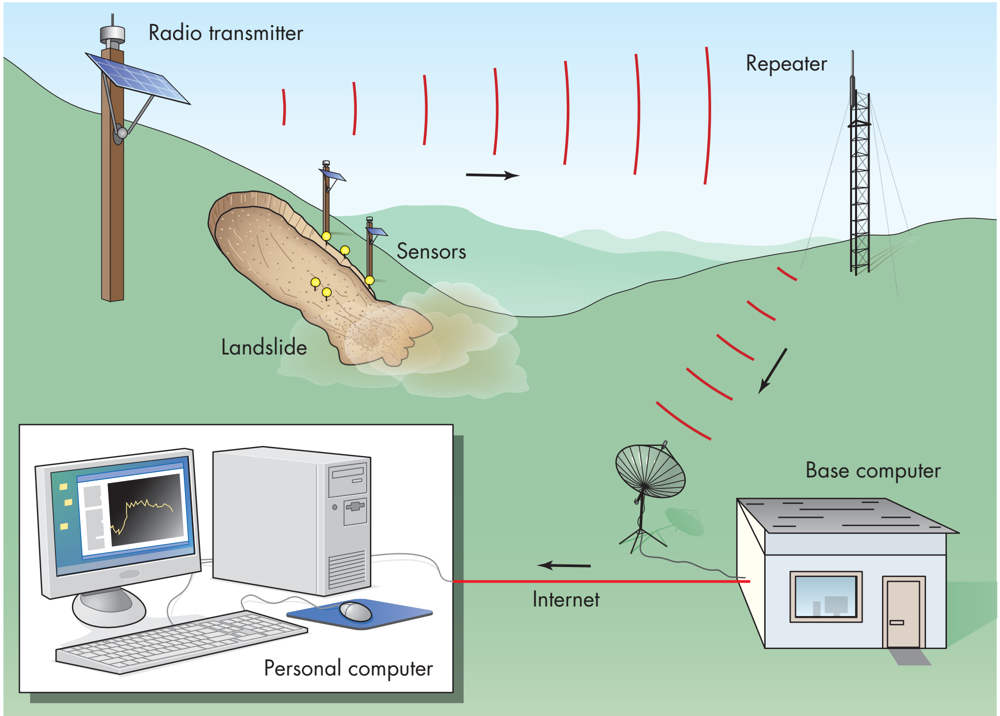
10.7 Subsidence

Interactions between geologic conditions and human activity have been factors in numerous incidents of **subsidence**, the very slow to rapid sinking or settling of Earth materials (Figure 10.5k). Most subsidence is caused either by the withdrawal of fluids from subsurface reservoirs or by the collapse of surface and near-surface soil and rocks over subterranean voids.

Withdrawal of Fluids

The withdrawal of fluids—such as oil with associated gas and water, groundwater, and mixtures of steam and water for geothermal power—can cause subsidence.[20] In all cases, the general principles are the same: Fluids in Earth materials below Earth's surface have a high fluid pressure that tends to support the material above. This is why a large rock at the bottom of a swimming pool seems lighter: Buoyancy produced by the liquid tends to lift the rock. If support or buoyancy is removed from Earth materials through pumping out of the fluid, the support is reduced, and surface subsidence may result.

Thousands of square kilometers of the central valley of California have subsided as a result of overpumping groundwater in the area (**Figure 10.26a**, page 355). More than 5,000 km^2 (1,930 mi^2) in the Los Banos–Kettleman City area alone have subsided more than 0.3 m (1 ft). Within this area, one stretch of valley 113 km (70 mi) long has subsided an average of more than 3 m (10 ft), with a maximum of about 9 m (30 ft) (Figure 10.26b). As the water was mined, the pore pressure was reduced and the grains were compacted;[21,22] the effect at the surface was



(a)

(b)

FIGURE 10.24 Real-time monitoring of active landslides (a) Idealized diagram of how real-time landslide data are collected by sensors and transmitted to people. (b) Geologist measuring landslide movement. *(Courtesy of Richard La Husen/USGS)*

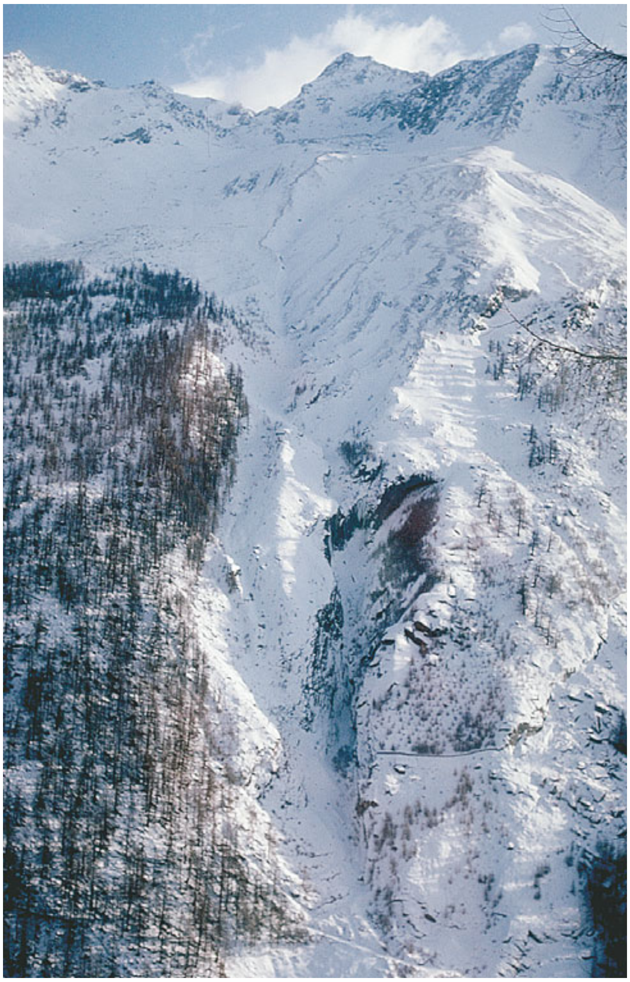
subsidence (**Figure 10.27**, page 356). Similar examples of subsidence caused by overpumping are documented near Phoenix, Arizona; Las Vegas, Nevada; Houston–Galveston, Texas; and Mexico City, Mexico. The subsidence can cause extremely long, deep surface fissures (open cracks) to form in sediments.[22]

Sinkholes

Subsidence is also caused by removal of subterranean Earth materials by natural processes. Voids—large open spaces such as caves—often form by chemical weathering within soluble rocks, such as limestone, dolomite, and evaporite rocks such as gypsum and salt. The resulting lack of support for overlying rock may cause it to collapse. The result is the formation of a **sinkhole**, a circular area of subsidence caused by the collapse of a near-surface subterranean void or room in a cavern.

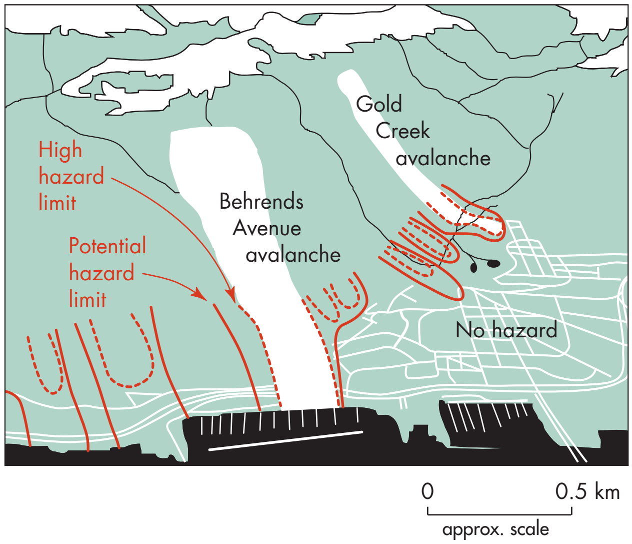
The popular news media (newspapers, TV, and Internet) often report about sinkholes. However these sources, in addition to referring to sinkholes as defined above, often refer to sinkholes as a more general process of subsidence of a road, building parking lot, etc. due to a break in a water line or subsurface drain line (example sewer line) that washes out subsurface sediment leaving a subsurface hole or void. Collapse over the void results in collapse at the surface, reported as a sinkhole.

Sinkholes have caused considerable damage to highways, homes, sewage facilities, and other structures. Natural or artificial fluctuations in the water table are probably the trigger mechanism. High water table conditions enlarge the cavern closer to the surface of Earth by dissolving material, and the buoyancy of the water helps support the overburden. Lowering of the water table eliminates some of the buoyant support and facilitates collapse. On



(a)

FIGURE 10.25 Avalanche hazard (a) Avalanche chute or track in the Swiss Alps. *(Edward A. Keller)* (b) Map of part of Juneau, Alaska, showing the avalanche hazard. *(After Cupp, D. 1982.* National Geographic *162:290–305)*

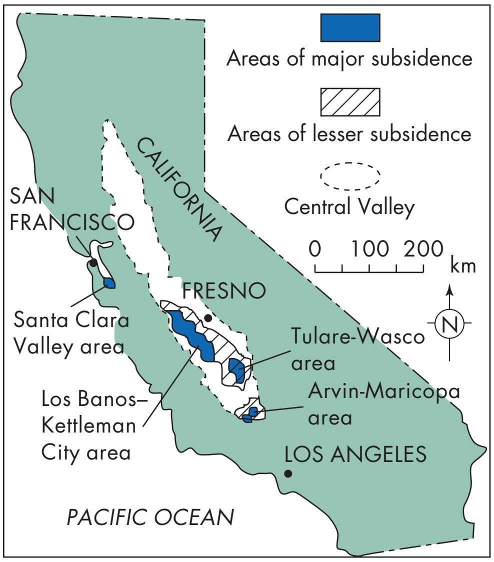


(b)

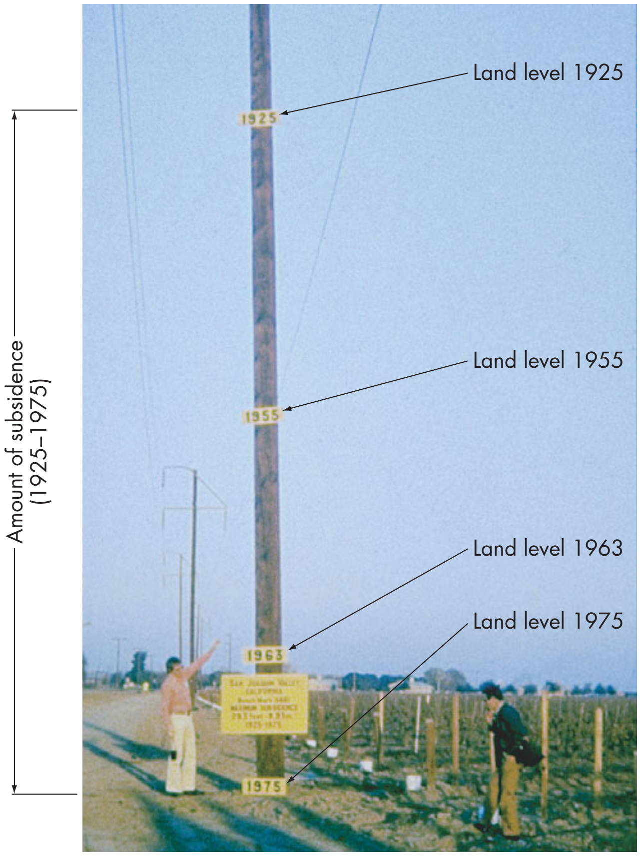
May 8, 1981, this process was dramatically illustrated in Winter Park, Florida, when a large sinkhole began developing. The sink grew rapidly for 3 days, swallowing part of a community swimming pool, parts of two businesses, several automobiles, and a house (**Figure 10.28**, page 357). Damage caused by the sinkhole exceeded $2 million. Sinkholes form nearly every year in central Florida when the groundwater level is lowest. The Winter Park sinkhole formed during a drought, when groundwater levels were at a record low. Although the exact positions of sinkholes cannot be predicted, their occurrence is greater during droughts; in fact, several smaller sinkholes developed at about the same time as the Winter Park event.[23] On June 23, 1986, a large subsidence pit developed at the site of an unrecognized, filled sinkhole in Lehigh Valley near Allentown, in eastern Pennsylvania. Within a period of only a few minutes, the collapse left a pit approximately 30 m (100 ft) in diameter and 14 m (46 ft) deep. Fortunately, the damage was confined to a street, parking lots, sidewalks, sewer lines, water lines, and utilities. Seventeen residences adjacent to the sinkhole narrowly escaped damage or loss; subsequent stabilization and repair costs were nearly $500,000. **Figure 10.29** (page 357) shows the generalized geology of Lehigh Valley. The northern part of the valley is underlain by shale, whereas the southern portion is underlain by limestone. The valley is bounded by resistant sandstone rocks to the north and resistant Precambrian igneous rocks to the south (Figure 10.29).[24]

Photographs from the 1940s to 1969 provide evidence of the sinkhole's history. In the 1940s, the sinkhole was delineated by a pond approximately 65 m (213 ft) in diameter. By 1958, the pond had dried up, the sinkhole was covered by vegetation, and the surrounding area was planted in crops. Ground photographs in 1960 suggest that people were using the sinkhole as a site to dump tree stumps, blocks of asphalt, and other trash. By 1969, there was no surface expression of the sinkhole; it was completely filled, and corn was planted over it.

Even though the sinkhole was completely filled with trash and other debris, it continued to receive



(a)



(b)

FIGURE 10.26 Land subsidence from groundwater extraction (a) Principal areas of land subsidence in California resulting from groundwater withdrawal. *(After Bull, W. B. 1973.* Geological Society of America Bulletin 84. *Reprinted by permission)* (b) Photograph illustrating the amount of subsidence in the San Joaquin Valley, California. The marks on the telephone pole are the positions of the ground surface in recent decades. The photo shows nearly 8 m (26 ft) of subsidence. *(Courtesy of Ray Kenny)*

runoff water that was later increased in volume by urbanization. Sources of water included storm runoff from adjacent apartments and townhouses, streets, and parking lots. It is also suspected that an old, leaking water line contributed to runoff into the sinkhole area. In addition, urbanization placed increased demand on local groundwater resources, resulting in the lowering of the water table. Geologists believe that hydrologic conditions contributed to the sudden failure. The increased urban runoff facilitated the loosening or removal of the plug—that is, the soil, clay, and trash that filled the sinkhole—while the lowering of the groundwater reduced the overlying support, as was the case with the Winter Park sinkhole. Sinkholes are discussed further in Chapter 13, with groundwater processes.

Salt Deposits

Serious subsidence events have been associated with salt mining. Salt is often mined by solution methods: Water is injected through wells into salt deposits, the salt dissolves, and water supersaturated with salt is pumped out. Because the removal of salt leaves a cavity in the rock and weakens support for the overlying rock, it may lead to large-scale subsidence.

On November 21, 1980, a bizarre example of subsidence associated with a salt mine occurred in southern Louisiana. Lake Peigneur, a shallow lake with an average depth of 1 m (3.3 ft), drained after the collapse of the salt mine below it. The collapse occurred after an oil-drilling operation apparently punched a hole into an abandoned mine shaft of the Jefferson Island Salt Dome, a still-active multimillion-dollar salt mine located about 430 m (1,410 ft) below the surface. As water entering the mine enlarged the hole, pillars of salt were scoured and dissolved, causing the roof of the mine to collapse and producing a large subsidence pit (**Figure 10.30**, page 358).

The lake drained so fast that 10 barges, a tugboat, and an oil-drilling barge disappeared in a whirlpool

of water into the mine. Fortunately, the 50 miners and 7 people on the oil rig escaped. The subsidence also claimed more than 0.25 km^2 (0.1 mi^2) of Jefferson Island, including historic botanical gardens, greenhouses, and a $500,000 private home. The remaining gardens were disrupted by large fractures that dropped the land down to the new edge of the lake. These fractures are formed as the land sinks and are commonly found on the margins of large subsidence pits.

Lake Peigneur immediately began refilling with water from a canal connecting it to the Gulf of Mexico, and nine of the barges popped to the surface 2 days later. There was fear at first that even greater subsidence would take place as pillars of salt holding up the roof of the salt dome dissolved. However, the hole was apparently sealed by debris in the form of soil and lake sediment that was pulled into the mine. Approximately 15 million m^3 (530 million ft^3) of water entered the salt dome, and the mine was a total loss. The previously shallow lake now has a large, deep hole in the bottom, which undoubtedly will change its aquatic ecology. In a 1983 out-of-court settlement, the salt-mining company was reportedly compen-

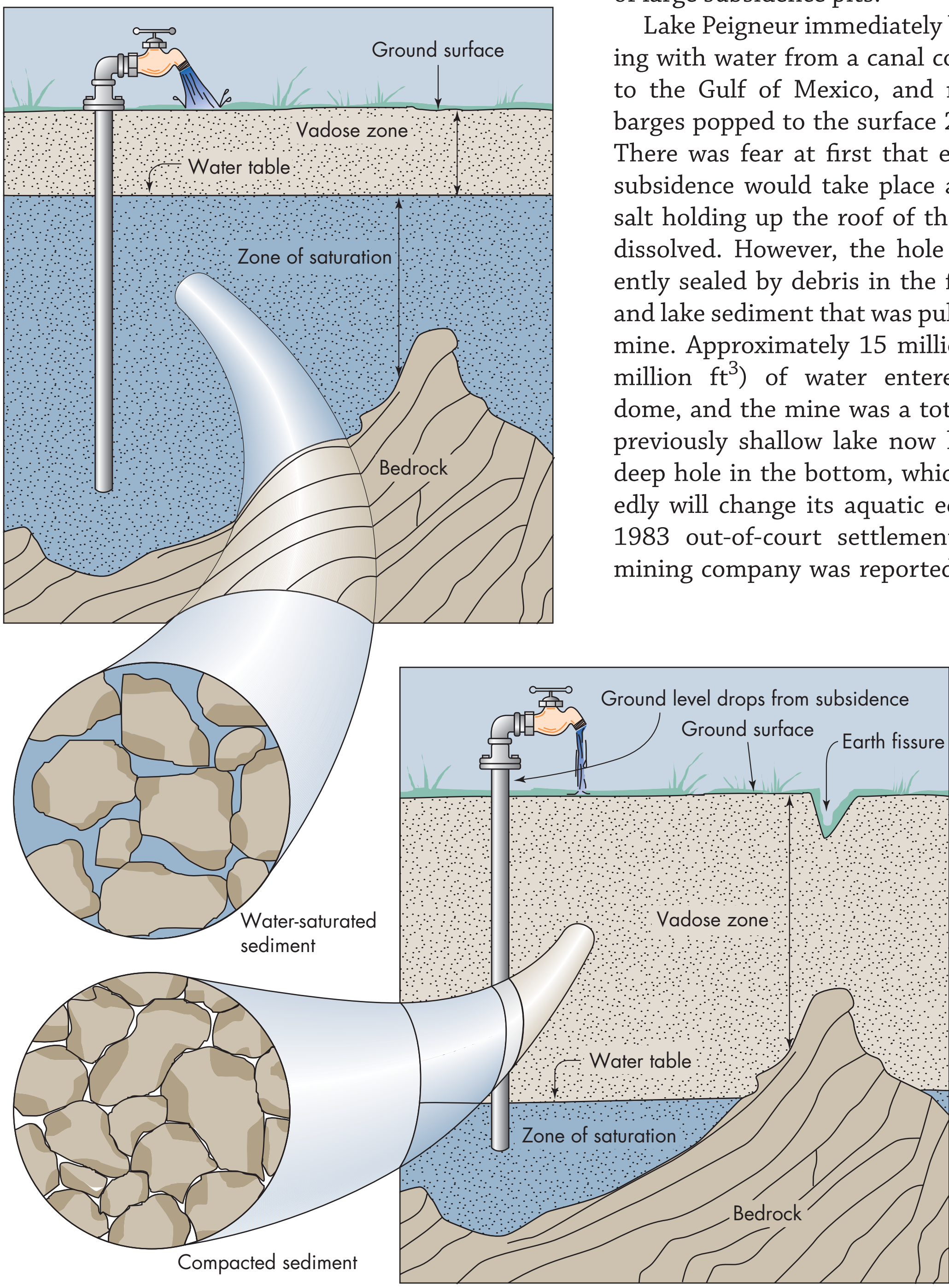


FIGURE 10.27 Process of subsidence Idealized diagram showing how surface subsidence results from pumping groundwater. The vadose zone is the unsaturated zone above the water table. The zone of saturation lies beneath the water table. Pore (empty) spaces between grains collapse after pumping. *(From Kenny, R. 1992. Fissures.* Earth *2(3):34–41)*

FIGURE 10.28 Sinkhole swallows part of a town This Winter Park, Florida, sinkhole grew rapidly for 3 days, swallowing part of a community swimming pool as well as two businesses, a house, and several automobiles. *(Leif Skoogfors/Woodfin Camp & Associates)*

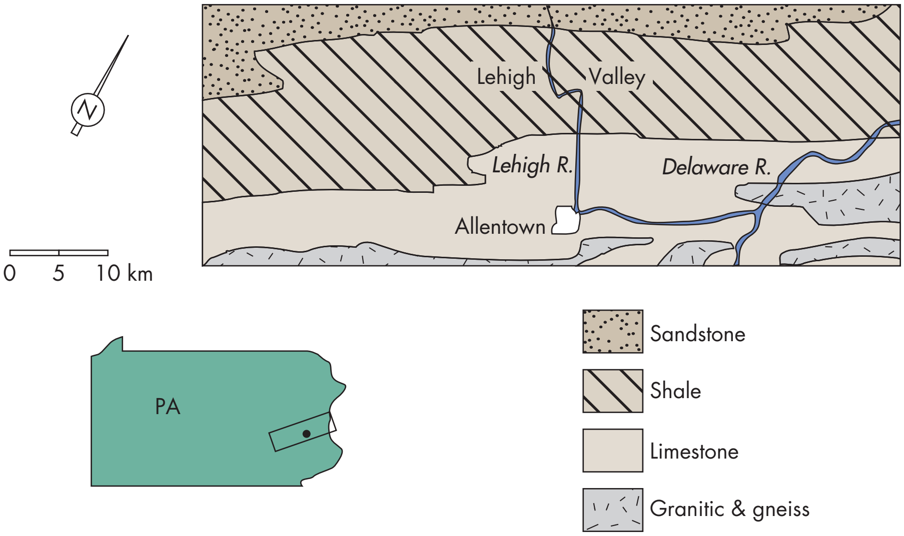


FIGURE 10.29 Geology of a valley with sinkhole hazard Generalized geologic map of the Lehigh Valley in eastern Pennsylvania, where a large collapse sinkhole formed suddenly. *(Modified from Dougherty, P. H., and Perlow, M., Jr. 1987.* Environmental Geology and Water Science *12(2):89–98)*

sated $30 million by the oil company involved. The owners of the botanical garden and private home apparently were compensated $13 million by the oil company, drilling company, and mining company.

The flooding of the mine raises important questions concerning the structural integrity of salt mines. The federal Strategic Petroleum Reserve Program is planning to store 75 million barrels of crude oil in an old salt mine of the Weeks Island salt dome about 19 km (12 mi) from Jefferson Island. Although the role of the draining of Lake Peigneur in the collapse is very significant, few salt domes have lakes above them. The Jefferson Island subsidence was thus a rare event.

Coal Mining

Subsurface mining of coal in the western and eastern United States has produced serious subsidence problems. The subsidence is most common where underground mining is close to the surface of the land or where the rocks left as pillars after mining are weak or intensely fractured. Usually, only 50 percent of the coal is removed, leaving the remainder as pillars that support the roof, formed from the rocks overlying the mine. Over time, the pillars weather, weaken, and collapse, producing the surface subsidence.[25] In the United States, more than 8,000 km^2 (3,090 mi^2) of land has subsided due to underground coal mining, and subsidence continues today, long after mining has terminated. In 1995, a coal mine that was last operated in the 1930s collapsed beneath a 600 m (1,970 ft) length of Interstate Highway 70 in Ohio; repairs took 3 months.[25] Subsidence most often affects farmland and rangelands but has also damaged buildings and other structures in towns and cities, including Scranton, Wilkes-Barre, and Pittsburgh, Pennsylvania (**Figure 10.31**).[6,25]

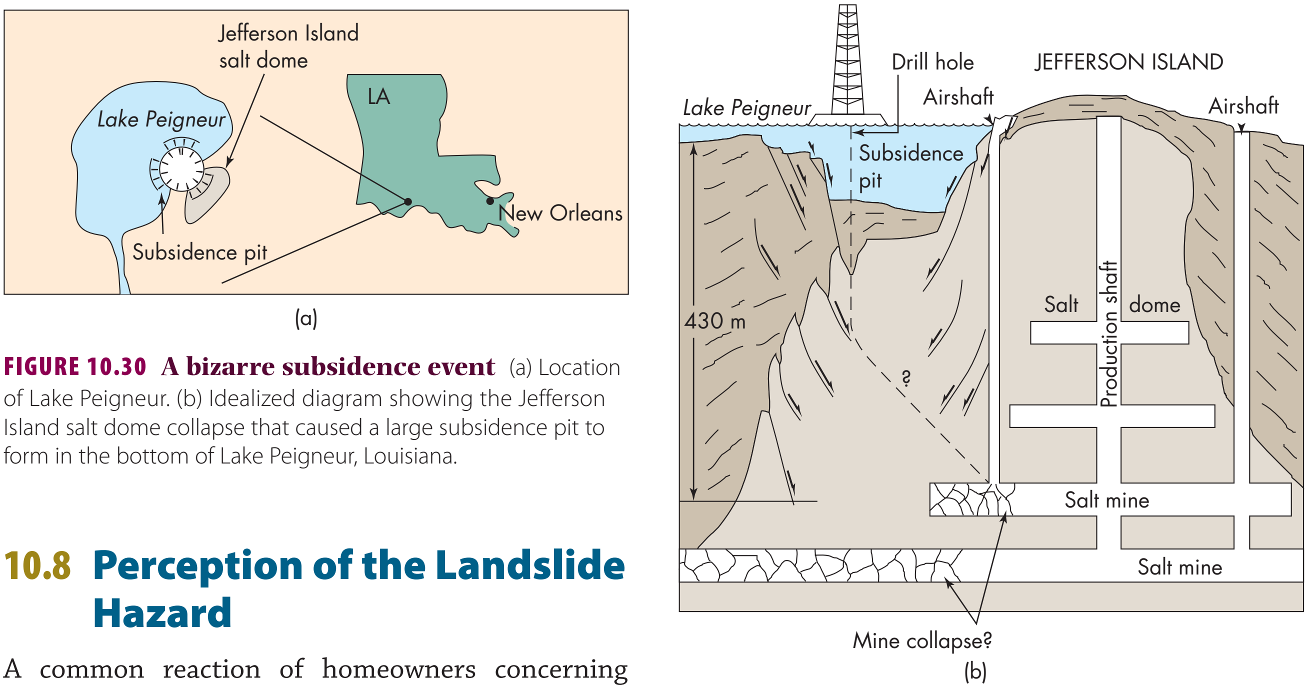


FIGURE 10.30 A bizarre subsidence event (a) Location of Lake Peigneur. (b) Idealized diagram showing the Jefferson Island salt dome collapse that caused a large subsidence pit to form in the bottom of Lake Peigneur, Louisiana.

10.8 Perception of the Landslide Hazard

A common reaction of homeowners concerning landslides is, "It could happen on other hillsides, but never this one."[14] Just as flood hazard mapping does not prevent development in flood-prone areas, landslide hazard maps will probably not prevent all people from moving into hazardous areas. Prospective hillside occupants who are initially unaware of the hazards may not all be swayed by technical information. The infrequency of large slides tends to reduce awareness of the hazard where evidence of past events is not readily visible. Unfortunately, it often takes catastrophic events that claim numerous expensive homes to bring the problem to people's attention. In the meantime, people in many parts of the Rocky Mountains, Appalachian Mountains, California, and other areas continue to build homes in areas subject to future landslides.

FIGURE 10.31 Subsidence over coal mines An underground fire in an abandoned coal mine in Pennsylvania has melted the snow near this vent. Note the smoke escaping to the atmosphere. *(National Institute for Occupational Safety & Health)*

What You Can Do to Minimize Your Landslide Hazard

Consider the following advice if purchasing property on a slope:

- Landslides often involve complex geology, and a geologic evaluation by a professional geologist of any property on a slope is recommended.
- Avoid homes at the mouth of a canyon, even a small one, where debris flows or mudflows may originate from upstream slopes and travel down the canyon.
- Consult local agencies, such as city or county engineering departments, that may be aware of landslides in your area.
- Watch out for "little landslides" in the corner of the property—they usually get larger with time.

- If purchasing a home, look for cracks in house walls and for retaining walls that lean or are cracked. Be wary of doors or windows that stick or floors that are uneven. Check foundations for cracks or tilting. If cracks in the walls or the foundation can be followed to the land outside the house, be especially concerned that a landslide may be present.
- Be wary of leaks in a swimming pool, trees tilted downslope, and utility wires that are taut or sagging.
- Be wary if small springs are present, as landslides tend to leak water. Look for especially "green areas," where more subsurface water is present.
- Walk the property and surrounding property, if possible, looking for linear or curved cracks (even small ones) that might indicate incipient instability of the land.
- Active landslides often have hummocks or steplike ground features.
- Fixing a potential landslide problem is often cost-effective, but it can still be expensive, and much of the fix is below ground, where you will never see the improvement. It is better to not purchase land with a potential landslide hazard!

The presence of one or more of these features is not proof of the presence of a landslide. For example, cracks in walls and foundations can be caused by soils that shrink and swell. However, further investigation is warranted if the above features are present.

Making The Connection

Linking the Opening Case History About La Conchita to the Fundamental Concepts

Consider and discuss the following questions:

1. What will be the likely role of human population and land use in La Conchita over the next 50 years if nothing is done?
2. How are science and values linked to reducing the landslide hazard at La Conchita?
3. Can La Conchita be a sustainable community over the next 100 years? How?
4. What can be learned from the landslide hazard at La Conchita that is applicable to other locations with a potential landslide hazard?

Summary

Landslides and related phenomena cause substantial damages and loss of life. Although they are natural events, their occurrence can be increased or decreased by human activity.

The most common landforms are slopes—dynamic, evolving systems in which surface material is constantly moving downslope, or mass wasting, at rates varying from imperceptible creep to thundering avalanches. Slope failure may involve flowage, slumping, sliding, or falling of Earth materials; landslides are often complex combinations of sliding and flowage.

The forces that produce landslides are determined by the interactions of several variables: the type of Earth material on the slope, topography and slope angle, climate, vegetation, water, and time. The cause of most landslides can be determined by examining the relations between forces that tend to make Earth materials slide, the driving forces, and forces that tend to oppose movement, the resisting forces. The most common driving force is the weight of the slope materials, and the most common resisting force is the strength of the slope materials. The factor of safety (FS) of a slope is the ratio of resisting forces to driving forces; a ratio A FS greater than about 1.25 means that the slope is likely stable. If the FS is between 1 and 1.25, the slope is conditionally stable. A FS less than 1 indicates potential slope failure. The type of rock or soil on a slope influences both the type and the frequency of landslides.

Water has an especially significant role in producing landslides. Water in streams, lakes, or oceans erodes the base of slopes, increasing the driving forces. Excess water increases the weight of the slope materials while raising the water pressure. Increased water pressure, in turn, decreases the resisting forces in the slope materials. The effects of human use on the magnitude and frequency of landslides vary from insignificant to very significant. When landslides occur independently of human activity, we need to

learn enough about them to avoid development in hazardous areas or to provide protective measures. In other cases, when human use has increased the number and severity of landslides, we need to learn how to minimize these occurrences. In some cases, dams and reservoirs have increased migration of groundwater into slopes, resulting in slope failure. Logging operations on weak, unstable slopes have increased landslide erosion. Grading of slopes for development has created or increased erosion problems in many urbanized areas of the world.

Minimizing landslide hazards requires identification, prevention, and correction procedures. Monitoring and mapping techniques facilitate identification of hazardous sites. Identification of potential landslides has been used to establish grading codes, and landslide damage in these areas has been decreased. Prevention of large natural slides is very difficult, but careful engineering practices can do much to minimize the hazard when it cannot be avoided. Engineering techniques for landslide prevention include drainage control, proper grading, and construction of supports, such as retaining walls. Correction of landslides must attack the processes that started the slide; this usually means initiating a drainage program that lowers water pressure in the slope.

Snow avalanches present a serious hazard on snow-covered, steep slopes. Loss of human life due to avalanches is increasing as more people venture into mountain areas for winter recreation.

Withdrawal of fluids, such as oil and water, and subsurface mining of salt, coal, and other minerals have caused widespread subsidence. In the case of fluid withdrawal, the cause of subsidence is a reduction of water pressures that tend to support overlying Earth materials. In the case of solid-material removal, subsidence may result from loss of support for the overlying material. The latter situation may occur naturally when voids are formed in soluble rock, such as limestone, and the collapse of overlying Earth material produces sinkholes.

Most people perceive the landslide hazard as minimal, unless they have prior experience with landslides. Furthermore, hillside residents, like floodplain occupants, are not easily swayed by technical information. Nevertheless, the wise person will have a geologist inspect property on a slope before purchasing.

Revisiting Fundamental Concepts

Human Population Growth By 2050, the world's population will have increased by about 50 percent. Having 3 billion more people to feed and house will place increased stress on the environment. More people will be living on steep slopes where landslides are likely to occur. Therefore, we must learn more about how to minimize the landslide hazard in order to reduce potential losses of human life and property.

Sustainability If we want future generations to inherit a quality environment, we must work to minimize the magnitude and frequency of human-induced landslides. When we remove trees from hill slopes or intensively urbanize hill slopes, landslides increase in both size and number. Landsliding is an erosion process, removing vegetation and soils, along with valuable land resources that future generations will need.

Earth as a System Hill slopes are complex systems with physical, chemical, hydrologic, biological, and human components. When we change one part of the system through land use change, we cause other changes that may affect the stability of the slope. This is an example of the principle of environmental unity. Slopes are very sensitive to changes in hydrology, and when trees are removed, the amount of water that infiltrates the soil or runs off the land changes. Trees use a lot of soil water through the process of transpiration, which is loss of water through leaves and other plant tissue. When trees or other vegetation are removed, this process stops, and the amount of water in the soil may increase. Wet slopes are more prone to landsliding than are dry slopes. If trees are logged, the roots may die and decay. When they do, the soil loses some strength because root systems bind the soil together. The combined effects of wetter soils and reduced soil strength as tree roots decay result in more shallow landslides. This concept explains the significant increase in shallow landslides that occurs several years after logging.

Hazardous Earth Processes, Risk Assessment, and Perception People are basically optimistic about where they wish to live, and their perception of landslide risk reflects this optimism. Education about potential risks and construction of hazard maps are necessary to help inform people about the potential hazards of hillside development.

Scientific Knowledge and Values Physical, chemical, and biological processes operating on hill slopes are fairly well understood. We also know the risks associated with hillside development and the methods to reduce the landslide hazard. As more people in the future are forced by economics or lured by the view to live in hazardous areas on steep hill slopes, we need to examine our values. How can we provide safe housing for growing urban areas, especially in developing countries? Too often

"shantytowns" develop on undesirable steep lands that have been cleared of forest. These areas, when hit by intense rainstorms or shaken by earthquakes, commonly produce slides that may kill hundreds to thousands of people. This scenario does not have to be replayed again and again if we place value on human life and apply principles of sound land use planning for people moving to urban centers.

Key Terms

factor of safety (FS) (p. 334)
landslide (p. 331)
mass wasting (p. 331)
rotational slide (p. 334)
sinkhole (p. 353)
snow avalanche (p. 351)
subsidence (p. 352)
translational slide (p. 334)

Review Questions

1. What is a landslide?
2. What are the main ways that materials on a slope may fail?
3. What is the factor of safety, and how is it defined?
4. Differentiate between rotational slides (slumps) and translational slides and shallow slips.
5. How does the slope angle affect the incidence of landslides?
6. What are the three ways that vegetation is important in slope stability?
7. How may spontaneous liquefaction occur?
8. Why does time play an important role in landslides?
9. What is the main lesson learned from the Vaiont Dam disaster?
10. How might the process of urbanization increase or decrease the stability of slopes?
11. What are the main steps we can take to prevent landslides?
12. What is the process that causes subsidence due to withdrawal of fluid, such as groundwater or petroleum?
13. What was the role of groundwater in the formation of the Winter Park sinkhole?

Critical Thinking Questions

1. Your consulting company is hired by a national park in your region to estimate the future risk from landsliding. Develop a plan of attack that outlines what must be done to achieve this objective.
2. Why do you think that many people are not easily swayed by technical information concerning hazards such as landslides? Assume that you have been hired by a community to make the citizens more aware of the landslide hazard in their very steep topographic area. Outline a plan of action and defend it.

Companion Website

www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Lifeguard rescuing a young girl at a New Jersey beach from dangerous surf generated by offshore Hurricane Danielle in late August 2010. *(Mel Evans/AP Photo)*

11 Coastal Processes

Learning Objectives

In this chapter, we focus on one of the most dynamic environments on Earth—the coast, where the sea meets the land. The beauty of the coastal zone, with its salty smells and the sight and sound of wind and waves striking the land, has inspired poets and artists for thousands of years. Beaches composed of sand or pebbles and rocky coastlines continue to attract tourists like few other areas. Yet most of us have little understanding of how ocean waves form and change the coastlines of the world. A major purpose of this chapter is to remove the mystery of how coastal areas are formed and maintained, while retaining the wonder. We seek to understand the hazards resulting from wind, waves, and storms, and how we can learn to live in the ever-changing coastal environment while sustaining its beauty. We will focus on the following learning objectives:

- **Know the basic terminology of waves and the processes of waves**
- **Be able to define the basic components of a beach**
- **Understand the process of littoral transport of sediment**
- **Know what rip currents are and why they are a serious hazard to swimmers**
- **Know the major processes related to coastal erosion**
- **Understand the various engineering approaches to shoreline protection**
- **Understand how human activities affect coastal erosion**
- **Understand why we are at a crossroads with respect to adjustments to coastal erosion**
- **Understand what tropical cyclones are and the hazards they produce**

Case History

The Cape Hatteras Lighthouse Controversy

In North Carolina, a dramatic collision of opinions concerning beach erosion was played out in recent years. Historically, North Carolina had adhered to the philosophy that beach erosion is a natural process with which its residents can live. When erosion began to threaten the historic Cape Hatteras Lighthouse (**Figure 11.1a**), this philosophy was tested. The lighthouse is located near Buxton, on North Carolina's barrier islands known as the Outer Banks.

When the lighthouse was originally constructed in the late nineteenth century, it was approximately 500 m (1,640 ft) from the sea. By the early 1990s, it was only 100 m (328 ft) away from the sea and in danger of being destroyed by a major storm. Officials in the area had to weigh the following options:

- Artificially control coastal erosion at the site and reverse state policy of yielding to erosion. The U.S. Army Corps of Engineers originally proposed to protect the lighthouse by constructing a $5.6 million seawall around the base.[1]
- Do nothing and eventually lose the lighthouse and, thus, an important bit of American history.
- Move the lighthouse inland. Many local people opposed this plan, fearing that the lighthouse would collapse if moved.[1]

Following much discussion, argument, and controversy over what to do, the National Park Service made the decision to move the lighthouse inland approximately 500 m (1,640 ft) from the eastern shore of Hatteras Island at a cost of about $12 million. The decision to move the lighthouse was based on several factors. It was consistent with the philosophy of flexible coastal zone planning to avoid hazardous zones rather than attempting to control natural processes. It was also consistent with North Carolina's policy to preserve historic objects, such as the lighthouse, for the enjoyment of future generations. The lighthouse was successfully moved during the summer of 1999 (Figure 11.1b). Given the present rate of coastal erosion, the lighthouse should be safe in its new location until the middle or end of the twenty-first century. Hurricane Dennis struck the island in 1999, after the lighthouse was moved, and the historic structure was not significantly damaged.[2]

Another lighthouse battle is looming on the East Coast. Hundreds of homes and other buildings along the coast on Long Island, New York, are now close to the actively eroding shore line. Included is the famous Montauk Lighthouse (**Figure 11.2**), which was constructed in 1796 on a bluff 100 m (328 ft) from the ocean and is now about 25 m (82 ft) from the ocean. One group argues for an improved hard structure, consisting of a multimillion-dollar, 280 m (920 ft)-long rock revetment (i.e., rock seawall) to protect the base of the bluff from erosion. Another group is arguing to move the lighthouse inland. Moving the lighthouse would be a challenge, and the rock revetment might change the coastline, causing problems in adjacent areas. The rock solution might also set a precedent for hard structural control of beach erosion on Long Island and other East Coast areas.

11.1 Introduction to Coastal Hazards

Coastal areas are dynamic environments that vary in their topography, climate, and vegetation. Continental and oceanic processes converge along coasts to produce landscapes that are characteristically capable of rapid change. The East Coast of the United States is a passive margin coastline far from a convergent plate boundary (see Chapter 2). The coastline is characterized by a wide continental shelf with barrier islands with wide, sandy beaches. Rocky coastlines are mostly restricted to the New England coast, where the Appalachian Mountains merge with the Atlantic Ocean. The West Coast is close to the convergent boundary between the North American and Pacific plates (i.e., it is an active margin coast). Mountain building has produced

(a) (b)

FIGURE 11.1 Lighthouse is moved (a) Cape Hatteras Lighthouse before being moved. *(David T. Foster III/Newscom)* (b) Cape Hatteras Lighthouse being moved in the summer of 1999. *(Reuters)*

FIGURE 11.2 Montauk Lighthouse The Montauk Point Lighthouse is close to the edge of the sea cliff. There is controversy about whether the existing stone revetment (i.e., sea wall) should be improved or whether moving the lighthouse should be considered. *(Peter Arnold, Inc./Alamy)*

a coastline with sea cliffs and rocky coastlines. Long, sandy beaches are present but not as abundant as along the East Coast.

The impact of hazardous coastal processes is considerable because many populated areas are located near the coast. In the United States, it is expected that most of the population will eventually be concentrated along the nation's 150,000 km (93,000 mi) of shoreline, including the Great Lakes. Today, the nation's largest cities lie in the coastal zone, and approximately 75 percent of the population lives in coastal states.[3] Coastal problems will, thus, increase because so many more people will live in coastal areas where the hazards occur. Once again, our activities continue to conflict with natural processes! Hazards along the coasts may become compounded by the fact that global warming and the accompanying global rise in sea level are increasing the coastal

erosion problem. (Climate change and sea level rise are discussed in Chapter 18.)

The most serious coastal hazards are the following:

- Rip currents generated in the surf zone
- Coastal erosion, which continues to produce considerable property damage that requires human adjustment
- Tsunami, or seismic sea waves (discussed in Chapter 7), which are particularly hazardous to coastal areas of the Pacific Ocean
- Tropical cyclones, called *hurricanes* in the Atlantic and *typhoons* in the Pacific, which claim many lives and cause enormous amounts of property damage every year

11.2 Coastal Processes

Waves

Waves that batter the coast are generated by offshore storms, sometimes thousands of kilometers from the shoreline where they will expend their energy. Wind blowing over the water produces friction along the air–water boundary. Since the air is moving much faster than the water, the moving air transfers some of its energy to the water, resulting in waves. The waves, in turn, eventually expend their energy at the shoreline. The size of the waves produced depends on the following:

- The velocity, or speed, of the wind. The greater the wind velocity, the larger the waves.
- The duration of the wind. Storms of longer duration have more time to impart energy to the water, producing larger waves.
- The distance that the wind blows across the surface, or *fetch*. The longer the fetch, the larger the waves.

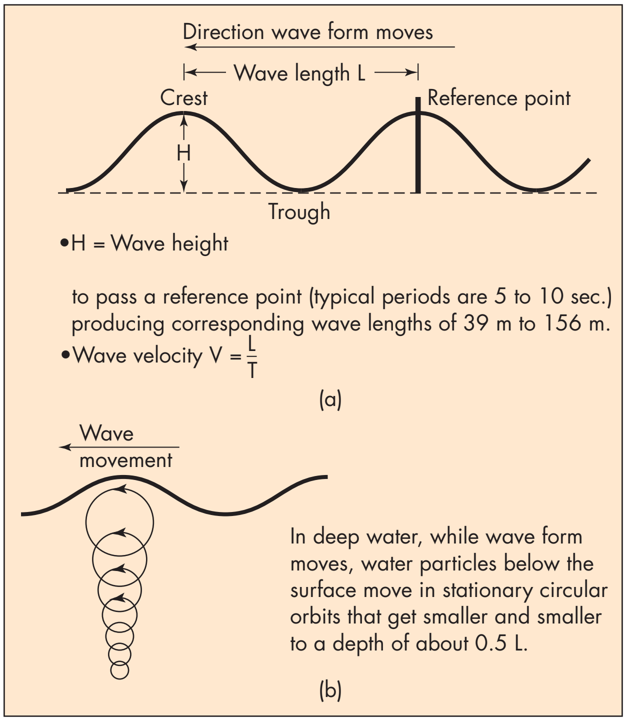
Within the area of the storm, the ocean waves have a variety of sizes and shapes, but, as they move away from their place of origin, they become sorted out into groups of similar waves. These groups of waves may travel for long distances across the ocean and arrive at distant shores with very little energy loss.

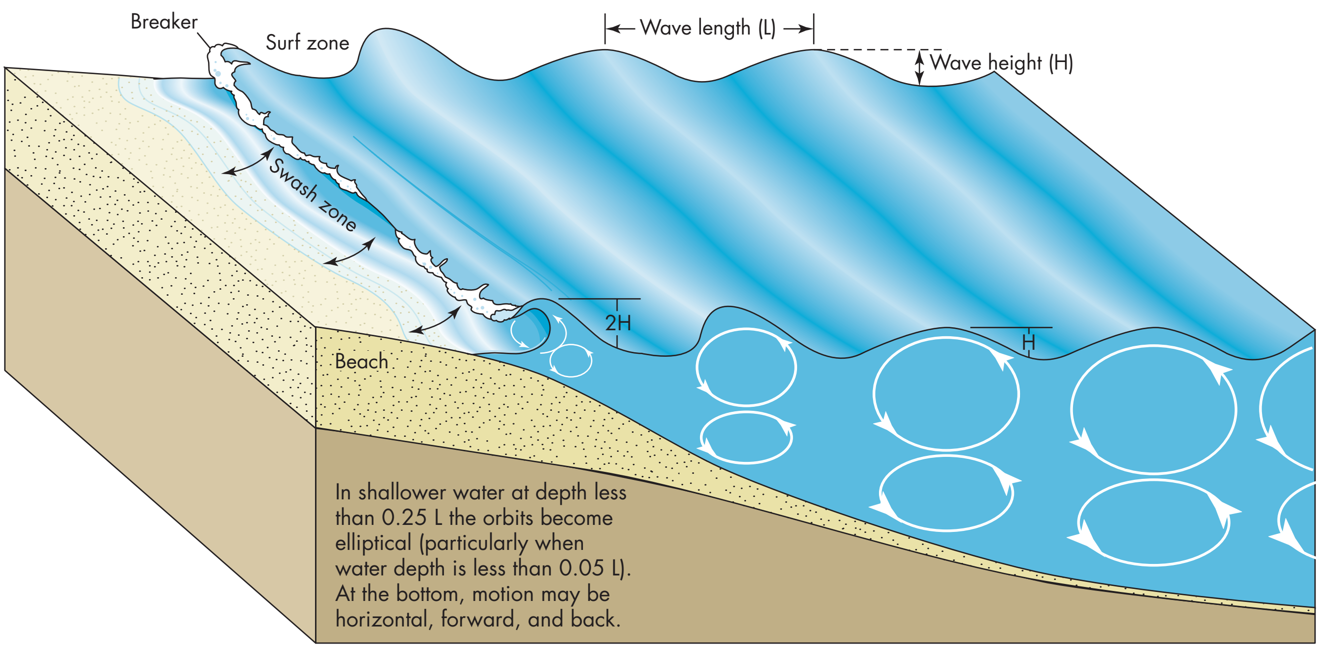
The basic shape, or wave form, of waves moving across deep water is shown in **Figure 11.3a**. The important parameters are *wave height*, which is the difference in height between the wave's trough and its peak, and *wave length*, the distance between successive peaks. The *wave period* (P) is the time in seconds for successive waves to pass a reference point. If you were floating with a life preserver in deep water and could record your motion as waves moved through your area, you would find that you bob up, down, forward, and back in a circular orbit, returning to about the same place. If you were below the surface with a breathing apparatus, you would still move in circles, but the circle would be smaller. That is, you would move up, down, forward, and back in a circular orbit that would remain in the same place while the waves traveled through. This concept is shown in Figure 11.3b. When waves enter shallow water at a depth of less than about one-half their wavelength (L), they "feel bottom." The circular orbits change to become ellipses; the motion at the bottom may be a very narrow ellipse, or essentially horizontal—that is, forward and back (Figure 11.3c). You may have experienced this phenomenon if you have stood or have swum in relatively shallow water on a beach and felt the water repeatedly push you toward the shore and then back out toward the sea.

The wave groups generated by storms far out at sea are called *swell*. As the swell enters shallower and shallower water, transformations take place that eventually lead to the waves breaking on the shore. For deep-water conditions, there are equations to predict wave height, period, and velocity based on the fetch, wind velocity, and length of time that the wind blows over the water. This information has important environmental consequences: By predicting the velocity and height of the waves, we can estimate when waves with a particular erosive capability generated by a distant storm will strike the shoreline.

We have said that waves expend their energy when they reach the coastline. But just how much energy are we talking about? The amount is surprisingly large. For example, the energy expended on a 400 km (250 mi) length of open coastline by waves with a height of about 1 m (3.3 ft) over a given period of time is approximately equivalent to the energy produced by one average-sized nuclear power plant over the same time period.[4] Wave energy is approximately proportional to the square of the wave height. Thus, if wave height increases to 2 m (6.6 ft), the wave energy increases by a factor of 2^2, or 4. If wave height increases to 5 m (16 ft), which is typical for large storms, then the energy expended,

FIGURE 11.3 Waves and beaches (a) Deep-water wave form (water depth is greater than 0.5 L, where L is wave length). The ratio of wave height to wave length is defined as wave steepness. If wave height exceeds about 10 percent (0.1) of the wave length, the wave becomes unstable and will break. Our drawing exaggerates wave height for illustrative purposes. The steepness of the waves in the drawing is about 1/3, or 0.33, which would be very unstable and would not exist long in nature. (b) Motion of water particles associated with wave movement in deep water. (c) Motion of water particles in shallow water at a depth less than 0.25 L. Water at the beach moves up and back in the swash zone, the very shallow water on the beach face.





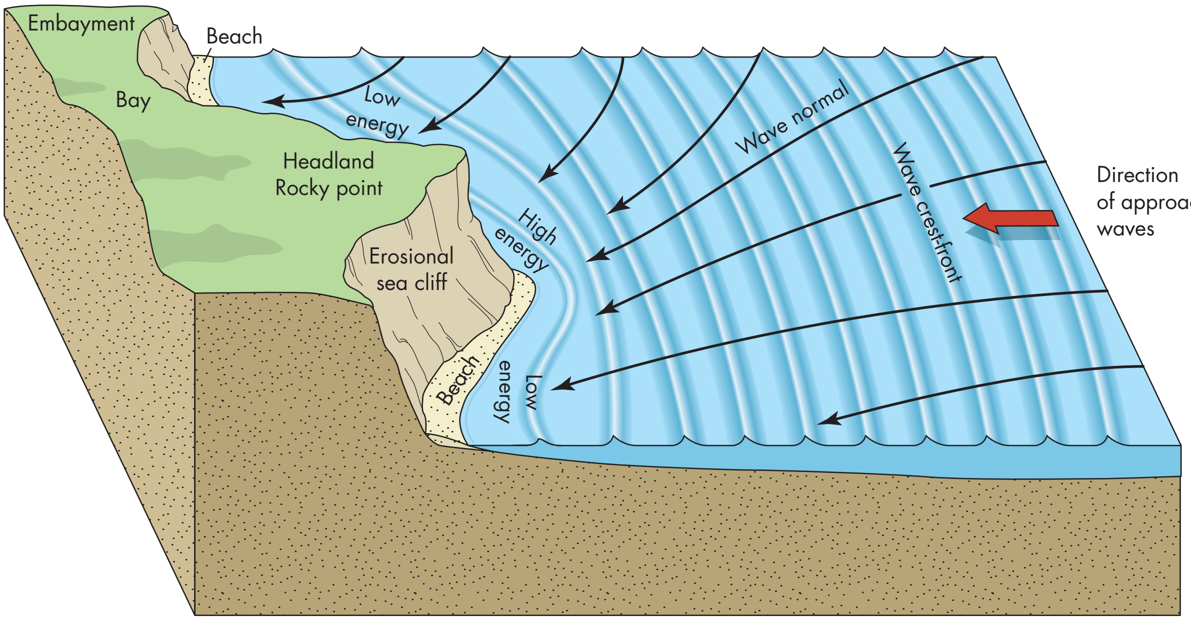
(c)

or wave power, increases 5^2, or 25 times over that of waves with a height of 1 m (3.3 ft).

When waves enter the coastal zone and shallow water, they impinge on the bottom and become steeper. Wave steepness is the ratio of wave height to wave length. Waves are unstable when the wave height is greater than about 10 percent (0.1) of the wave length. As waves move into shallow water, the wave period remains constant, but wave length and velocity decrease and wave height increases. The

waves change shape from rounded crests and troughs in deep water to peaked crests with relatively flat troughs in shallow water close to shore. Perhaps the most dramatic feature of waves entering shallow water is their rapid increase in height. The height of waves in shallow water, where they break, may be as much as twice their deep-water height (Figure 11.3c). Waves near the shoreline, just outside the surf zone, reach a wave steepness that is unstable. The instability causes the waves to break and expend their energy on the shoreline.[5]

Although wave heights offshore are relatively constant, the local wave height may increase or decrease when the *wave front* (see **Figure 11.4a**) reaches the near-shore environment. This change can be attributed to irregularities in the offshore topography and the shape of the coastline. Figure 11.4a is an idealized diagram showing a rocky point, or headland, between two relatively straight reaches of coastline. The offshore topography is similar to that of the coastline. As a wave front approaches the coastline, the shape of the front changes and becomes more parallel to the coastline. This change occurs because, as the waves enter shallow water, they slow down first where the water is shallowest, that is, off the rocky point. The result is a bending, or *refraction*, of the wave front. In Figure 11.4a, the lines drawn perpendicular to the wave fronts, with arrows pointing



(a)

(b)

FIGURE 11.4 Convergence and divergence of wave energy (a) Idealized diagram of the process of wave refraction and concentration of wave energy at rocky points, or headlands. The refraction, or bending of the wave fronts, causes the convergence of wave normals on the rocky point and divergence at the bay. (b) Photograph of large waves striking a rocky headland. *(Rhonda R/Shutterstock)*

toward the shoreline, are known as *wave normals*. Notice that, due to the bending of the wave fronts by refraction, there is a *convergence* of the wave normals at the headland, or rocky point, and a *divergence* of the wave normals at the beaches, or embayments. Where wave normals converge, wave height increases; as a result, wave energy expenditure at the shoreline also increases. Figure 11.4b shows a photograph of large waves striking a rocky headland.

The long-term effect of greater energy expenditure on protruding areas is that wave erosion tends to straighten the shoreline. The total energy from waves reaching a coastline during a particular time interval may be fairly constant, but there may be considerable local variability of energy expenditure when the waves break on the shoreline. In addition, breaking waves may peak up quickly and plunge or surge, or they may gently spill, depending on local conditions, such as the steepness of the shoreline (**Figure 11.5**) and the height and length of waves arriving at the shoreline from a distant storm. *Plunging breakers* tend to be highly erosive at the shoreline, whereas *spilling breakers* are more gentle and may facilitate the deposition of sand on beaches. The large plunging breakers that occur during storms cause much of the coastal erosion we observe.

Beach Form and Beach Processes

A **beach** is a landform consisting of loose material, such as sand or gravel, that has accumulated by wave action at the shoreline. Beaches may be composed of a variety of loose material in the shore zone, the composition of which depends on the environment. For example, many Pacific island beaches include broken bits of shell and coral; Hawaii's black sand beaches are

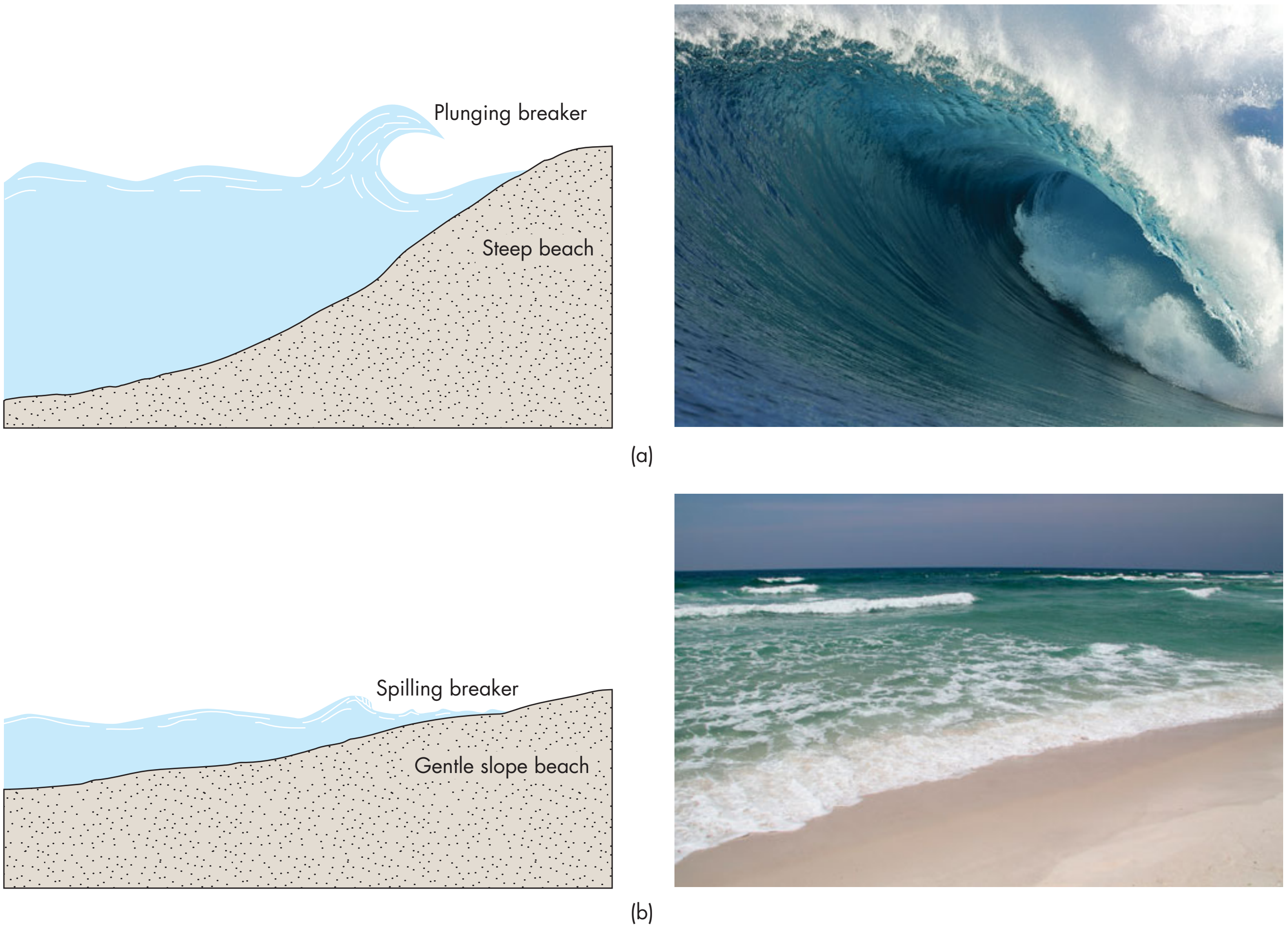


FIGURE 11.5 Types of breakers Idealized diagram and photographs showing (a) plunging breakers on a steep beach and (b) spilling breakers on a gently sloping beach. *([a] Reniw-Imagery/iStockphoto [b] Laura Gangi Pond/Shutterstock)*

composed of volcanic rock; and grains of quartz and feldspar are found on the beaches of southern California. Figure 11.6 shows the basic terminology of an idealized near-shore environment. The landward extension of the beach terminates at a natural topographic and morphologic change such as a sea cliff or a line of sand dunes. The *berms* are flat backshore areas on beaches formed by deposition of sediment as waves rush up and expend the last of their energy. Berms are where you will find people sunbathing. The *beach face* is the sloping portion of the beach below the berm, and the part of the beach face that is exposed by the uprush and backwash of waves is called the *swash zone*. The *surf zone* is that portion of the seashore environment where turbulent translational waves move toward the shore after the incoming waves break; the *breaker zone* is the area where the incoming waves become unstable, peak, and break. The *longshore trough* and *longshore bar* are an elongated depression and adjacent ridge of sand produced by wave action. A particular beach, especially if it is wide and gently sloping, may have a series of longshore bars, longshore troughs, and breaker zones.[5]

Transport of Sand

The sand on beaches is not static; wave action keeps the sand moving along the beach in the surf and swash zones. A longshore current is produced by incoming waves striking the coast at an angle (Figure 11.7). Because the waves strike the coast at an angle, a component of wave energy is directed along the shore. If waves arrive at a beach perfectly parallel to the beach, then no longshore current is generated. The longshore current is a stream of water flowing parallel to the shore in the surf zone. This current can be surprisingly strong. If you are swimming on a beach and wading in and out of the surf zone, you may notice that the longer you go in and out through the surf zone, the further away you are from where you started and left your beach towel and umbrella. As you move in and out through the surf and swash zone, the current will move you along the coast, and the sand is doing exactly the same thing.

The process that transports sand along the beach, called **longshore sediment transport**, has two components: (1) Sand is transported along the coast with the longshore current in the surf zone; and (2) the up-and-back movement of beach sand in the swash zone causes the sand to move along the beach in a zigzag path (Figure 11.7). Most of the sand is transported in the surf zone by the longshore current.

The direction of transport of sand along beaches in the United States is generally from the north to the south for beaches on both the East and West Coasts of the country. Although most of the transport is to the south, it can be variable and depends upon the wave action and in which direction the waves strike the shore. The amount of sand transported along a beach, whether we are talking about Long Island, New York, or Los Angeles, California, is surprisingly large, at several hundred thousand cubic meters of sediment per year. However, the amount of sand transported on a given day or period of days is extremely variable. On many days little sand is transported, and on others the amount is much larger. Most of the sediment is transported during storms by larger waves.

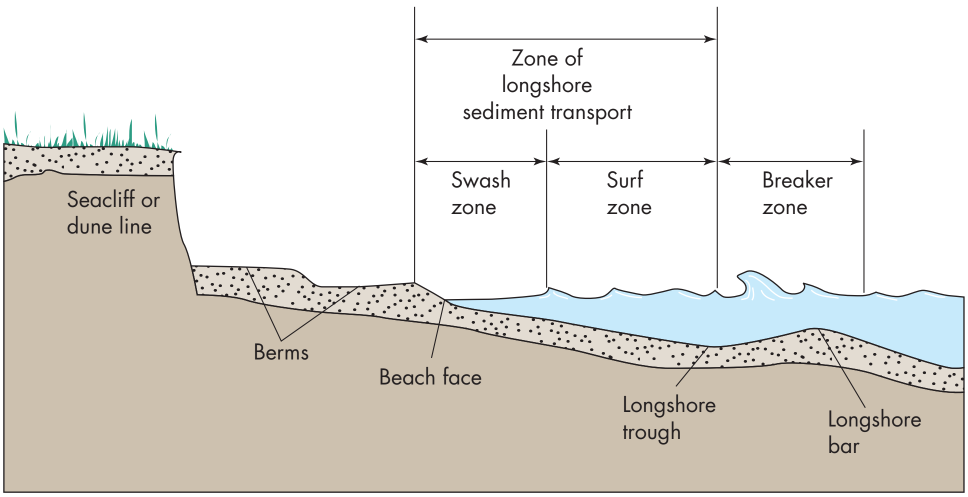


FIGURE 11.6 Beach terms Basic terminology for landforms and wave action in the beach and near-shore environment.

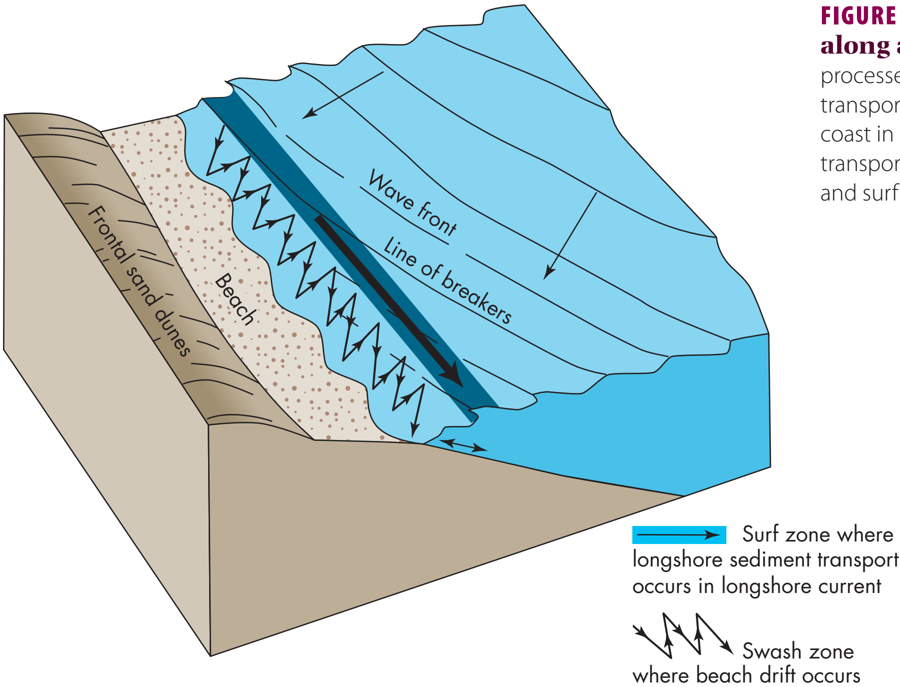


FIGURE 11.7 Transport of sediment along a coast Block diagram showing the processes of beach drift and longshore sediment transport, which collectively move sand along the coast in a process known as longshore sediment transport. Sediments transported in the swash zone and surf zone follow paths shown by the arrows.

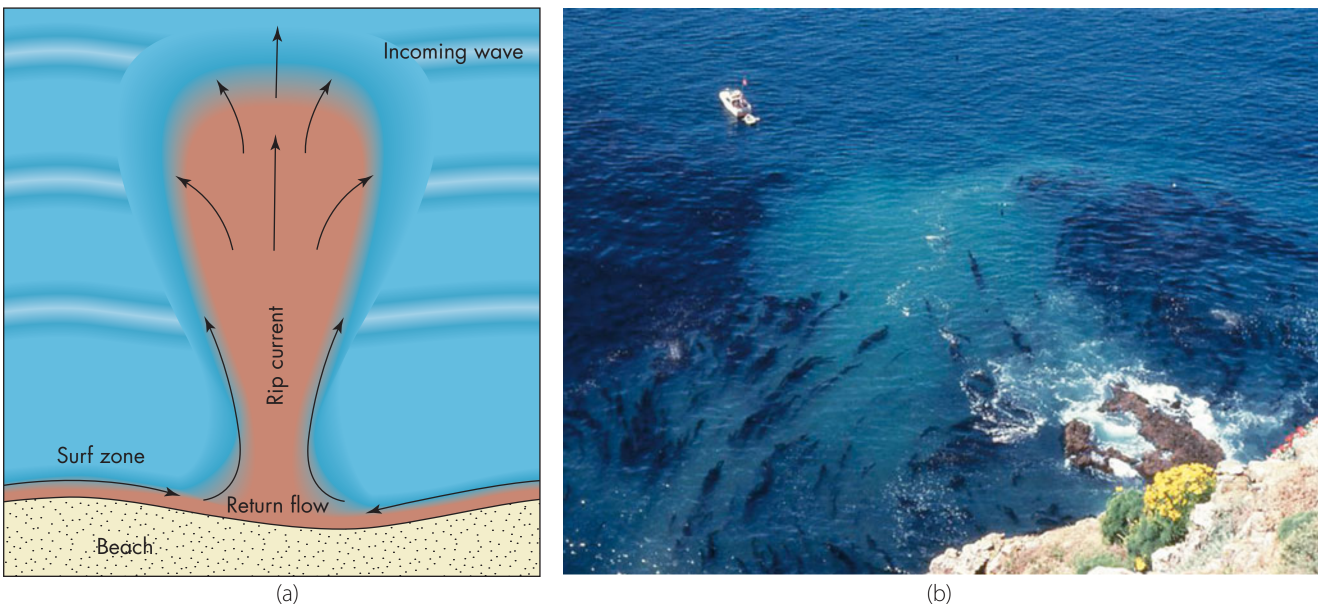


FIGURE 11.8 Rip current (a) Bird's-eye view of the surf zone, showing a rip current, which is the return flow of water that forms as a result of incoming waves. (b) Rip current at Santa Cruz Island, California. The floating kelp shows the rip current. *(Edward A. Keller)*

Rip Currents

When a series of large waves arrives at a coastline and breaks on the beach, the water tends to pile up on the shore. The water does not return as it came in, along the entire shoreline, but is concentrated in narrow zones known as **rip currents** (Figure 11.8). Beachgoers and lifeguards call them *riptides* or *undertow*. They certainly are not tides, and they do not pull people under the water, but they can pull people offshore. In the United States, up to 200 people are killed and 20,000 people are rescued from rip currents each year. In late August 2010, more than 100 people were rescued from the surf from North Carolina to New Jersey over a 2-day

period when waves from offshore Hurricane Danielle sent high waves and rough surf to the coast (see opening photograph). Therefore, it is clear that rip currents constitute a serious coastal hazard to swimmers, killing more people in the United States on an annual basis than do hurricanes or earthquakes; the number of deaths caused by rip currents is equivalent to the number caused by river flooding. People drown in rip currents because they do not know how to swim or because they panic and fight the current by trying to swim directly back to shore. Winning a fight with a rip current is nearly impossible because the current can exceed 6 km per hour (4 mi per hour), a speed that even strong swimmers cannot maintain for long. A swimmer trying to fight a rip current soon becomes exhausted and may not have the energy to keep swimming. Fortunately, rip currents are usually relatively narrow, a few meters to a few tens of meters wide, and they dissipate outside the surf zone, within tens to hundreds of meters offshore. To safely escape a rip current, a swimmer must first recognize the current and then swim parallel to the shore until he or she is outside the current. Only then should the swimmer attempt to swim back to shore. The key to survival is not to panic. When you swim in the ocean, watch the waves for a few minutes before entering the water and note the “surf beat,” the regularly arriving sets of small and larger waves. Rip currents can form quickly after the arrival of a set of large waves. They can be recognized as a relatively quiet area in the surf zone where fewer incoming waves break. You may see the current as a mass of water moving out through the surf zone. The water in the current may also be darker, carrying suspended sediment. Remember, if you get caught in a rip current, don’t panic; swim parallel to the shore until you are outside the current and then head back to the beach. If there are lifeguards in the area, yell for assistance!

11.3 Coastal Erosion

As a result of the global rise in sea level and inappropriate development in the coastal zone, coastal erosion is becoming recognized as a serious national and worldwide problem. Coastal erosion is generally a more continuous, predictable process than other natural hazards, such as earthquakes, tropical cyclones, or floods, and large sums of money are spent in attempts to control it. If extensive development of coastal areas for vacation and recreational living continues, coastal erosion will certainly become a more serious problem.

Beach Budget

An easy way to visualize beach erosion at a particular beach is to take a **beach-budget** approach.[5] An analogy to the budget is your bank account. You deposit money at regular or not-so-regular times. Some money is in storage, and that’s your account balance; you periodically withdraw funds, which is output. Similarly, we can analyze a beach in terms of input, storage, and output of sand or larger sediment that may be found on the beach. Input of sediment to a beach occurs by coastal processes that move the sediment along the shore line (Figure 11.7) or produce sand from erosion of a sea cliff or sand dunes on the upper part of a beach. The sediment that is in storage on a beach is what you see when you visit the site. Output of sediment is the material that moves away from the site by coastal processes similar to those that brought the sediment to the beach. If input exceeds output, the beach will grow as more sediment is stored and the beach widens. If input and output are relatively equal to one another, the beach will remain in a rough equilibrium at about the same width. If output of sediment exceeds input, the beach will erode, and there will be fewer grains of sediment on the beach. Thus, we see that the budget represents a balance of sand on the beach over a period of years. Short-term changes in sediment supply due to the attack of storm waves will cause seasonal or storm-related changes to the supply of sediment on a beach. Long-term changes in the beach budget caused by climate change or human impact cause long-term growth or erosion of a beach. A simple beach budget is presented in A Closer Look: Beach Budget.

Erosion Factors

The sand on many beaches is supplied to the coastal areas by rivers that transport it from areas upstream, where it has been produced by weathering of quartz- and feldspar-rich rocks. We have interfered with this material flow of sand from inland areas to the beach by building dams that trap the sand. As a result, some beaches have become deprived of sediment and have eroded.

A Closer Look

Beach Budget

For a given shoreline segment, the total volume of sand added (gained) to the beach can be balanced (compared) to losses. This produces the "beach budget":[5]

- If losses are greater than gains, erosion results.
- If losses are less than gains, the beach grows by accretion of sand.
- We can evaluate a budget over a set period of time, such as 1 year or 10 years.

As an example, imagine a simple coast with rivers supplying sand, a sea cliff, a beach, and a submarine canyon (**Figure 11.A**). This coast defines a *littoral cell*, which is a segment of coast (i.e., a system) that includes sources and transport of sand to and along the beach. (In this simple case, rivers deliver sand, as does sea cliff erosion.) Sand is transported along the coast, and some is transported from the near-shore environment down a *submarine canyon* (i.e., an offshore canyon that may head into the surf zone and remove sand from the beach transport system). Here, we determine the budget before and after a dam was constructed, confirming the erosion observed on beaches south of the submarine canyon where homes are threatened.

To estimate the sediment delivered to the coast from the river, we can use equations (numerical models) or regional graphs.[5] The basin before the dam has an area contributing sediment of 800 km^2. From our analysis of sediment production, we estimate that the sediment delivered to the beach from the river is about 300 $m^3/km^2/yr$. Following dam construction, the sediment-contributing area is reduced to 500 km^2, with a yield of 400 $m^3/km^2/yr$. The increase per unit area results because smaller tributaries below the dam have a higher sediment yield.

Assume that 30 percent of sediment delivered from the river will remain on the beach and that it is sand sized and larger:

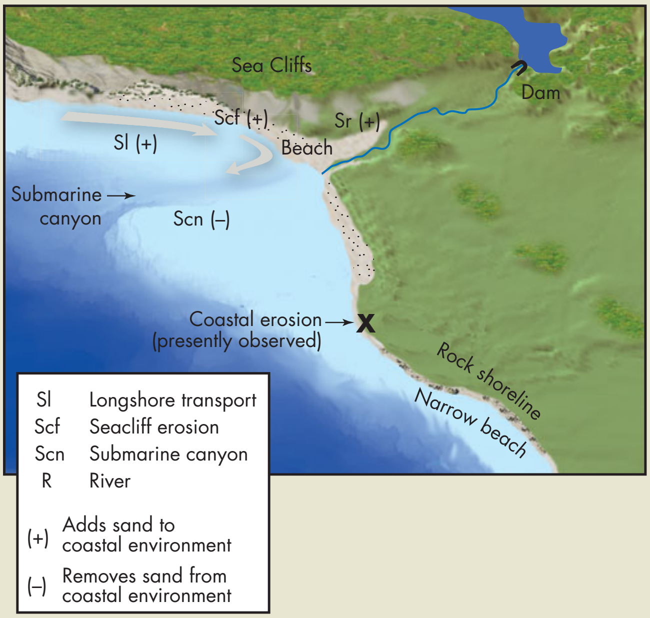
Before dam:

$$\begin{aligned} Sr\ (+) &= (300\ m^3/km^2/yr)(800\ km^2)(0.3) \\ &= 72{,}000\ m^3/yr \end{aligned}$$

After dam:

$$\begin{aligned} Sr\ (+) &= (400\ m^3/km^2/yr)(500\ km^2)(0.3) \\ &= 60{,}000\ m^3/yr \end{aligned}$$

Assume that there are several beach homes near point *X*. What advice would you give them? What would be your response if there were high-rise coastal resorts near point *X*?



Sources of sand for the beach budget example (+ = gain; – = loss):

Longshore transport (+)	South	200,000 m^3/yr
	North	50,000 m^3/yr
	Net	150,000 m^3/yr to south
(Scf) Sea cliff erosion (+)	Erosion rate is 0.5 m/yr; average height of sea cliff is 6 m; total length 3,000 m. Assume 50 percent of material eroded remains on beach.	
Scf = (0.5 m/yr)(6 m)(3,000 m)(0.5) = 4,500 m^3/yr		
(Sr) River source (+)	Assume drainage area of 800 km^2	
A dam was constructed 15 years ago, reducing the drainage basin delivering sediment to the coast to 500 km^2.		

FIGURE 11.A Beach budget Example of how a simple beach budget is constructed.

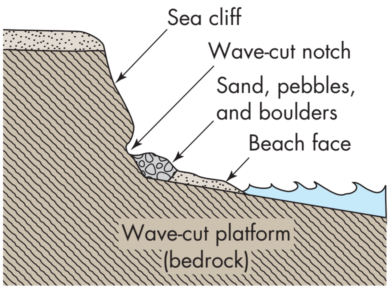
(Scy) Down submarine canyon (−):		
Estimated from offshore observations: 220,000 m^3/yr		
Budget before dam:		
Longshore drift (Sl)	+	150,000 m^3/yr
Cliff erosion (Scf)	+	4,500 m^3/yr
River (Sr)	+	72,000 m^3/yr
Submarine canyon (Scy)	−	220,000 m^3/yr
Budget +6,500 m^3/y; therefore, because more sand is arriving at point X on Figure 11.A than is leaving, the beach is growing.		
Budget after dam:		
Sl	+	150,000 m^3/yr
Scf	+	4,500 m^3/yr
Sr	+	60,000 m^3/yr
Scy	−	220,000 m^3/yr
Budget −5,500 m^3/yr; therefore, more sand is leaving point X than is arriving, and erosion is observed.		

Damming is not the only reason for erosion. For example, beach erosion along the East Coast can be the result of tropical cyclones (hurricanes) and severe storms, known as Northeasters or Nor'easters;[4] or a rise in sea level; or human interference with natural shore processes.[6] Sea level is rising around the world at the rate of about 2 to 3 mm (0.08 to 0.12 in.) per year, independent of any tectonic movement. Evidence suggests that the rate of rise has increased in recent decades. The increase is due to the melting of the polar ice caps and thermal expansion of the upper ocean waters, triggered by global warming that is in part related to increased atmospheric carbon dioxide produced by burning fossil fuels. Sea levels could rise by 20 cm to 2 m (8 to 80 in) over the next century, ensuring that coastal erosion will become an even greater problem than it is today.

Sea Cliff Erosion

When a **sea cliff** (i.e., a steep bluff or cliff) is present along a coastline, additional erosion problems may occur because the sea cliff is exposed to both wave action and land erosion processes, such as running water and landslides. These processes may work together to erode the cliff at a greater rate than either process could alone. The problem is further compounded when people interfere with the sea cliff environment through inappropriate development.

Figure 11.9 shows a typical southern California sea cliff environment at low tide. The rocks of the cliff are steeply inclined and folded shale. A thin veneer of sand and coarser material, such as pebbles and boulders, near the base of the cliff covers the wave-cut platform, which is a nearly flat bench cut into the bedrock by wave action. A mantle of sand approximately 1 m (3.3 ft) thick covers the beach during the summer, when long, gentle, spilling breakers construct a wide berm while protecting the sea cliff from wave erosion. During the winter, plunging breakers, which have a high potential to erode beaches, remove the mantle of sand and expose the base of the sea cliff. Thus, it is not surprising that most erosion of the sea cliffs in southern California takes place during the winter.



(a)

(b)

FIGURE 11.9 Sea cliff and beach (a) Generalized cross section and (b) photograph of sea cliff, beach, and wave-cut platform, Santa Barbara, California. *(Courtesy of Donald Weaver)*

(a)

(b)

FIGURE 11.10 Sea cliff erosion (a) The pipe in this photograph, from the early 1990s, carries surface runoff from the top of the sea cliff down to the beach. Notice that the house at the top of the sea cliff has a layer of cement partway down the cliff. The purpose of the cement is to retard erosion. (b) The same location in 2001. Note the landslide that has occurred, removing some of the cement and rock of the sea cliff. *(Edward A. Keller)*

A variety of human activities can induce sea cliff erosion. Urbanization, for example, results in increased runoff. If the runoff is not controlled, carefully collected, and diverted away from the sea cliff, serious erosion can result. Drainpipes that dump urban runoff from streets and homes directly onto the sea cliff increase erosion. Drainpipes that route runoff to the base of the sea cliff on the face of the beach result in less erosion (**Figure 11.10a**). Watering lawns and gardens on top of a sea cliff may add a good deal of water to the slope. This water tends to migrate downward through the sea cliff toward the base. When water emerges as small seeps or springs from a sea cliff, it effectively reduces the stability of the sea cliff, facilitating erosion, including landslides (Figure 11.10b).[7]

Structures, such as walls, buildings, swimming pools, and patios, near the edge of a sea cliff may

FIGURE 11.11 Students living on the edge Apartment buildings on the edge of the sea cliff in the university community of Isla Vista, California. The sign states that the outdoor deck is now open. Unfortunately, the deck is not particularly safe because it is overhanging the cliff by at least 1 m (3.3 ft). Notice the exposed cement pillars in the sea cliff, which were intended to help support the houses. These decks and apartment buildings are in imminent danger of collapsing into the sea. *(Edward A. Keller)*

also decrease stability by adding weight to the slope, increasing both small and large landslides (**Figure 11.11**). Strict regulation of development in many areas of the coastal zone now forbids most risky construction, but we continue to live with some of our past mistakes.

The rate of sea cliff erosion is variable, and few measurements are available. Near Santa Barbara, California, the rate of sea cliff erosion averages 15 to 30 cm (6 to 12 in.) per year. These erosion rates are moderate compared with those in other parts of the world. Along the Norfolk coast of England, for example, erosion rates in some areas are about 2 m (6.6 ft) per year. The rate of erosion is dependent on the resistance of the rocks and the height of the sea cliff.[6] The rate of coastal erosion can be determined by a new remote sensing technique called LiDAR (see A Closer Look: Measuring Coastal Change).

Sea cliff erosion is a natural process that cannot be completely controlled unless large amounts of time and money are invested, and, even then, there is no guarantee that erosion will cease. Therefore, it seems we must learn to live with some erosion. It can be minimized by applying sound conservation practices, such as controlling the water on and in the cliff and not placing homes, walls, large trees, or other structures that contribute to driving forces close to the top edge of a cliff.

11.4 Coastal Hazards and Engineering Structures

Efforts to stabilize a beach can be generalized into three approaches:

- **Hard stabilization:** Engineering structures to protect a shoreline from waves
- **Soft stabilization:** Adding sand to a beach (beach nourishment)
- **Managed retreat:** Living with beach erosion with, perhaps, a mixture of hard and soft stabilization

Hard Stabilization

Engineering structures in the coastal environment, including sea walls, groins, breakwaters, and jetties, are primarily designed to improve navigation or retard erosion. However, because they tend to interfere with the littoral transport of sediment along the beach, these structures all too often cause undesirable deposition and erosion in their vicinity.

A Closer Look

Measuring Coastal Change

Technology has recently provided a remote sensing method of measuring and monitoring changes in the coastal environment. Light Detection and Ranging (LiDAR) is an aircraft-mounted laser system that can record several tens of thousand elevation measurements per second, with vertical resolution of better than 15 cm (6 in.). Once a baseline set of elevations is recorded, subsequent flights can detect changes in the coastal zone, such as change in shape of the beach coastal dunes or sea cliff. **Figure 11.B** shows a digital elevation model determined by LiDAR for the Hilton Head, South Carolina, coastal area in the vicinity of a hotel that is very close to the active beach. **Figure 11.C** shows the sea cliff environment near Pacifica, California, where 12 homes were condemned as unsafe following winter storms in early 1998. The amount of sea cliff erosion from LiDAR from October 1997 to April 1998 is shown in **Figure 11.D**. Total erosion was about 10 m (30 ft) landward and 1 to 2 m on the beach. A method to determine a longer-term rate (say a decade or more) of sea cliff retreat (erosion of the top landward) is now possible. Aerial photographs (from different times) do not generally work well for measurement of the amount of coastal erosion. This results because even on large scale photographs it is difficult (if not impossible) to measure a few meters of erosion over a decade or so. What does work, assuming the rate is at close to 0.33 m (1 ft) per year or more, is to use two sets of LiDAR data taken a decade or more apart or using available LiDAR (say 10 years old) with a very accurate land survey (+/− 0.5 m) of the position of the top of the sea cliff today (such surveys are very possible using modern survey techniques). Superposing the two data sets (2 LiDAR or LiDAR and survey) can result in being able to confidently measure the amount and rate of sea cliff retreat +/− 0.5 m. It is possible because over a decade the amount of retreat is about 3 m, which is about 6 times the resolution. At this level, individual small landslides and other changes in the position of the top of the sea cliff become apparent.

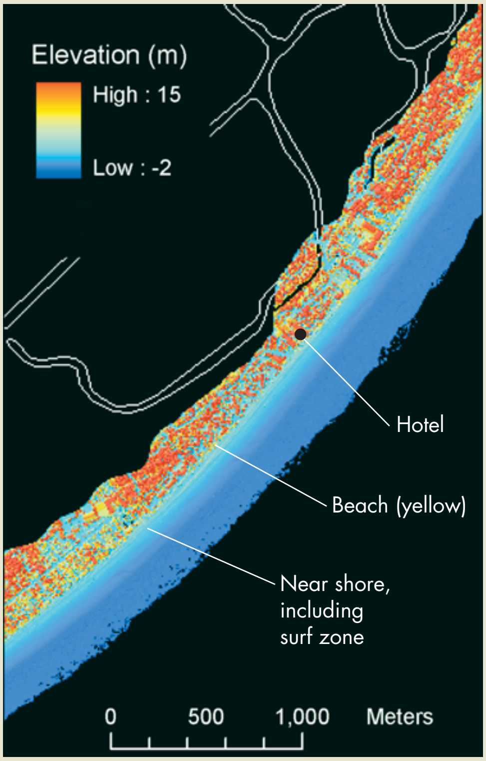


FIGURE 11.B Coastal topography Digital elevation map of part of Hilton Head, South Carolina. Data from Light Detection and Ranging (LIDAR), an aircraft-mounted laser remote-sensing technique. The hotel is very close to the beach source. *(Modified from NOAA, www.csc.noaa.gov/products/sccoasts/html/tutlid.htm)*

FIGURE 11.C Severe coastal erosion This erosion occurred near Pacifica, California, early in 1998. *(Courtesy of Monty Hampton/USGS)*

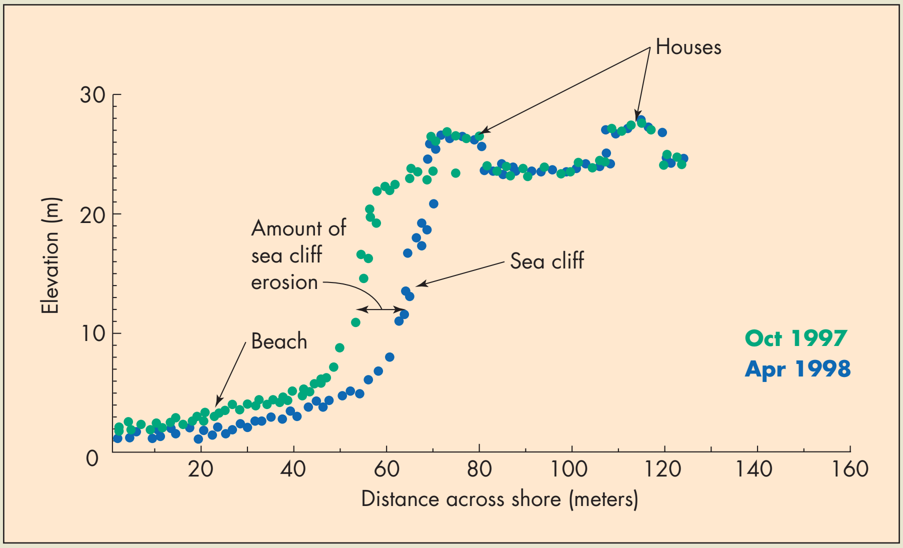
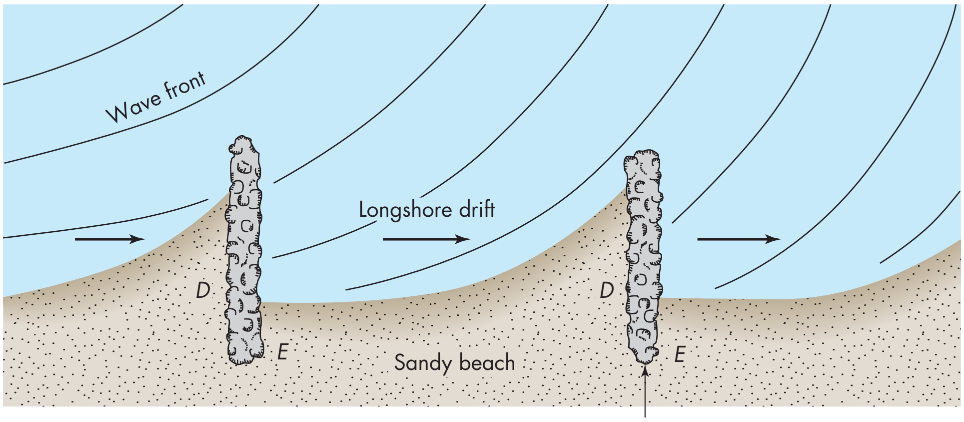


FIGURE 11.D Sea cliff erosion This sea cliff near Pacifica, California, has experienced about 10 m (30 ft) of erosion (LIDAR data). Several houses were condemned and seven were torn down. *(Modified after USGS 1998 http://coastal.er.usgs.gov/lidar/AGU_fall98)*

Sea walls. **Sea walls** are structures constructed parallel to the coastline to help retard erosion. They may be constructed of concrete, large stones, wood, or other materials. Sea walls constructed at the base of a sea cliff may not be particularly effective; considerable erosion of the sea cliff results from mass-wasting processes on the cliff itself (see Figure 11.10b), as well as wave erosion at the base. Sea wall use has been criticized because sea walls are often vertical structures that reflect incoming waves, or bounce them back from the shore. The reflection of waves enhances beach erosion and, over several decades, produces a narrower beach with less sand. Unless carefully designed to complement existing land uses, sea walls generally cause environmental and aesthetic degradation. In addition to causing a narrowing of a beach, sea walls may reduce biodiversity of the beach ecosystem (see Chapter 4). The design and construction of sea walls must be carefully tailored to specific sites. Some geologists believe that sea walls cause more problems than they solve and should be used rarely, if ever.[8]

Groins. **Groins** are linear structures placed perpendicular to the shore, usually in groups called *groin fields* (**Figure 11.12**). Each groin is designed to trap a portion of the sand that moves in the littoral transport system. A small accumulation of sand will develop updrift of each groin, thus building an irregular but wider beach. The wider beach protects the shoreline from erosion.

However, there is an inherent problem with groins: Although deposition occurs updrift of a groin, erosion tends to occur in the downdrift direction. Thus, a groin or a groin field results in a wider, more protected beach in a desired area but may cause a zone of erosion to develop in the adjacent downcoast shoreline. The erosion results because, as a groin traps sediment on its updrift side, the downdrift area is deprived of sediment. Once a groin has trapped all the sediment it can hold, sand in the groin is transported around its offshore end to continue its journey along the beach. Therefore, erosion may be minimized by artificially filling each groin. This process, known as **beach nourishment**, requires extracting sand from the ocean or other sources and placing it onto the beach. When nourished, the groins will draw less sand from the natural littoral transport system, and the downdrift erosion will be reduced.[5] Despite beach nourishment



(b)

(c)

FIGURE 11.12 Beach groins (a) Diagram of two beach groins. (b) Close-up of downdrift zone of erosion. (c) Updrift deposition (right) and downdrift erosion (left). Deposited sediment builds a wide beach in the updrift direction; in the downdrift direction, the sparse amount of sediment for transport can cause erosion. *(Edward A. Keller)*

and other precautions, groins may still cause undesirable erosion; therefore, their use should be carefully evaluated.

Breakwaters. Breakwaters and jetties protect limited stretches of the shoreline from waves. **Breakwaters** are designed to intercept waves and provide a protected area, or harbor, for boat moorings; they may be attached to, or separated from, the beach (**Figure 11.13a, b**). In either case, a breakwater blocks the natural littoral transport of beach sediment, causing the configuration of the coast to change locally as new areas of deposition and erosion develop. In addition to possibly causing serious erosion problems in the downdrift direction, breakwaters act as sand traps that accumulate sand in the updrift direction. Eventually the trapped sand may fill or block the entrance to the harbor as a deposit called a *sand spit* or *bar* develops. As a result, a dredging program, with an *artificial bypass*, is often necessary to keep the harbor open and clear of sediment. The sand that is removed by dredging, unless it is polluted, is transported in a pipe with water and released on the beach downdrift of the breakwater to rejoin the natural littoral transport system, thus reducing the erosion problem. It is the transport of the sand from the site where it is dredged to the downdrift location that is referred to as an artificial bypass.

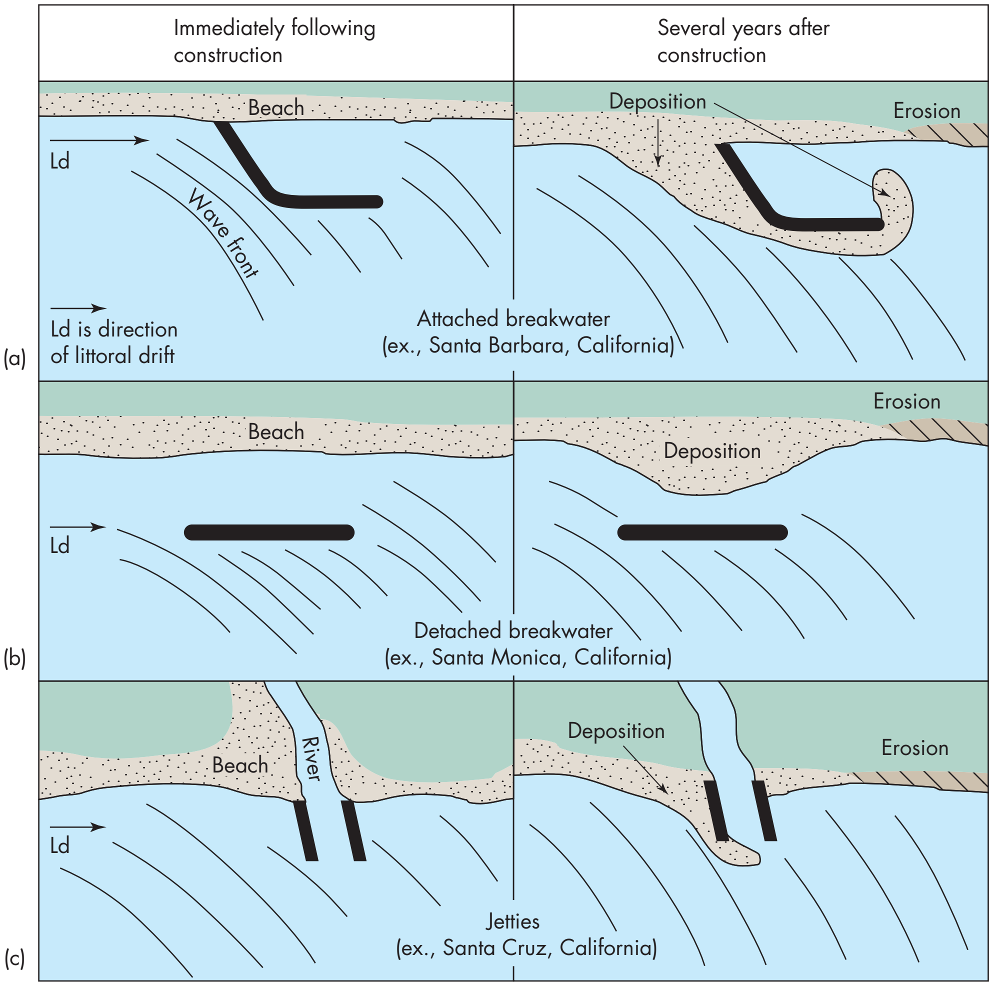


FIGURE 11.13 Engineering structures constructed in the surf zone cause change Diagrams illustrating the effects of breakwaters and jetties on local patterns of deposition and erosion.

Jetties. **Jetties** are often constructed in pairs at the mouth of a river or inlet to a lagoon, estuary, or bay (Figure 11.13c). They are designed to stabilize the channel, prevent or minimize deposition of sediment in the channel, and generally protect it from large waves.[5] Jetties tend to block the littoral transport of beach sediment, thus causing the updrift beach adjacent to the jetty to widen while downdrift beaches erode. The deposition at jetties may eventually fill the channel, making it useless, while downcoast erosion damages coastal development. Dredging the sediment minimizes but does not eliminate all undesirable deposition and erosion.

Unfortunately, it is impossible to build a breakwater or jetty that will not interfere with longshore movement of beach sediment. These structures must, therefore, be carefully planned and must incorporate protective measures that eliminate or at least minimize adverse effects. These protective measures may include installation of a dredging and artificial sediment-bypass system, a beach nourishment program, sea walls, riprap (i.e., large rocks), or some combination of these.[5]

Sometimes a hard solution is decided upon to stabilize a stretch of coast of particular value to people. Cities and other areas of land on a coast are an example where sea walls and other structures protect development and agriculture land. The classic example is the sea dikes that hold back the North Sea from the Netherlands. Dike building began in the Netherlands over 2,000 years ago.

Nearly 30 percent of the land area of the Netherlands (where about 16 million people live) is below sea level. Along the Normandy Coast of France, there is a coastal erosion project to protect Pointe du Hoc, which has particular historical significance. The work to minimize coastal erosion at the Pointe du Hoc is of interest because it involves careful evaluation of the local geology, linked to a hard solution. (See A Closer Look: Coastal Erosion at Pointe du Hoc, France.)

Soft Stabilization

Beach Nourishment: An Alternative to Engineering Structures. In the discussion above, we introduced the topic of beach nourishment as an adjunct to engineering structures in the coastal zone. Beach nourishment can also be an alternative to engineering structures. In its purest form, beach nourishment consists of artificially placing sand on beaches in the hope of constructing a positive beach budget. When you budget your money, you hope for a positive budget, allowing you some extra cash. Similarly, a positive beach budget means that when all the sand that enters and leaves the beach is accounted for, there is enough sand left to maintain the beach itself. Beach nourishment is sometimes referred to as "soft" stabilization to control beach erosion, as contrasted with "hard" stabilization, such as constructing groins or seawalls. Ideally, the presence of the nourished beach protects coastal property from the attack of waves.[5] The procedure has distinct advantages: It is aesthetically preferable to many engineering structures, and it provides a recreation beach, as well as some protection from shoreline erosion.

In the mid-1970s, the city of Miami Beach, Florida, and the U.S. Army Corps of Engineers began an ambitious beach nourishment program to reverse a serious beach erosion problem that had plagued the area since the 1950s. The program was also intended to provide protection from storms. The natural beach had nearly disappeared by the 1950s, and only small pockets of sand could be found associated with various shoreline protection structures, including sea walls and groins. As the beach disappeared, coastal resort areas, including high-rise hotels, became vulnerable to storm erosion.[8] The nourishment program was designed to produce a positive beach budget that would widen the beach and provide additional protection from storm damage. The project cost approximately \$62 million over 10 years and involved nourishment of about 160,000 m^3 (209,300 yd^3) of sand per year to replenish erosion losses. By 1980, about 18 million m^3 (23.5 million yd^3) of sand had been dredged and pumped from an offshore site onto the beach, producing a 200 m (656 ft)-wide beach.[10] **Figure 11.14** shows Miami Beach before and after the nourishment. The change is dramatic.

A cross-sectional design of the project shows the wide berm and frontal dune system, which is a line of sand dunes just above the high-tide line that functions as a buffer to wave erosion and storm surge (**Figure 11.15**). The Miami project was expanded in the mid- to late 1980s to include dune restoration, which involved establishing native vegetation on the dune. Special wooden walkways allow public access through the dunes, while other areas of the dunes are protected. The successful Miami Beach nourishment project has functioned for more than 20 years, surviving major hurricanes in 1979 and 1992,[5,8] and is certainly preferable to the fragmented erosion-control methods that preceded it.

More than 600 km (373 mi) of coastline in the United States have received some sort of beach nourishment. Not all of this nourishment has had the positive effects reported for Miami Beach. For example, in 1982, Ocean City, New Jersey, nourished a stretch of beach at a cost of just over \$5 million. After a series of storms that struck the beach, the sand was eroded in just 2.5 months. The beach sands at Miami may be eroded at a much greater cost. Beach nourishment remains controversial, and some consider beach nourishment nothing more than "sacrificial sand" that will eventually be washed away by coastal erosion.[8] Miami Beach is an exception with respect to its apparent success, and our discussion oversimplifies positive aspects of nourishment. The annual cost to nourish Miami Beach is about \$3 million. More than 20 million tourists visit the beach each year. Foreign tourism alone brings in about \$2 billion per year, over 650 times the cost of the nourishment.

Important issues of finding sand compatible with the site, how the nourishment will be paid for, and

FIGURE 11.14 Beach nourishment Miami Beach (a) before and (b) after beach nourishment. *(Courtesy of U.S. Army Corps of Engineers)*

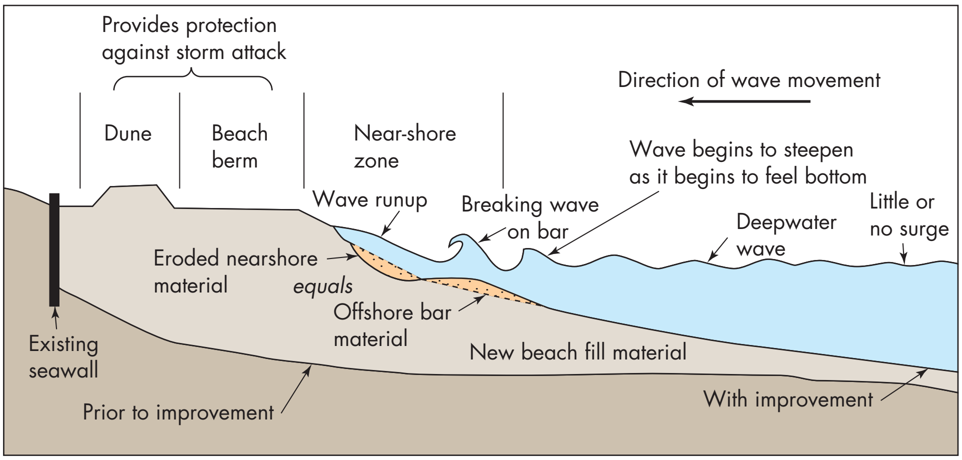


FIGURE 11.15 Miami Beach shape after nourishment Cross section of the Miami Beach nourishment project. The dune and beach berm system provide protection against storm attack. *(Courtesy of U.S. Army Corps of Engineers)*

possible disruption of beach ecosystems must be carefully evaluated prior to any nourishment project. Nevertheless, beach nourishment has become a preferred method of restoring or even creating recreational beaches and protecting the shoreline from coastal erosion around the world. Additional case histories are needed to document the success or failure of the projects. Also needed is more public education to inform people of what can be expected from beach nourishment.[5]

11.5 Human Activity and Coastal Erosion: Some Examples

Human interference with natural shore processes has caused considerable coastal erosion. Most problems arise in areas that are highly populated and developed. As we have discussed, artificially constructed barriers often retard the movement of sand, causing beaches to grow in some areas and erode in others, resulting in damage to valuable beachfront property.

A Closer Look

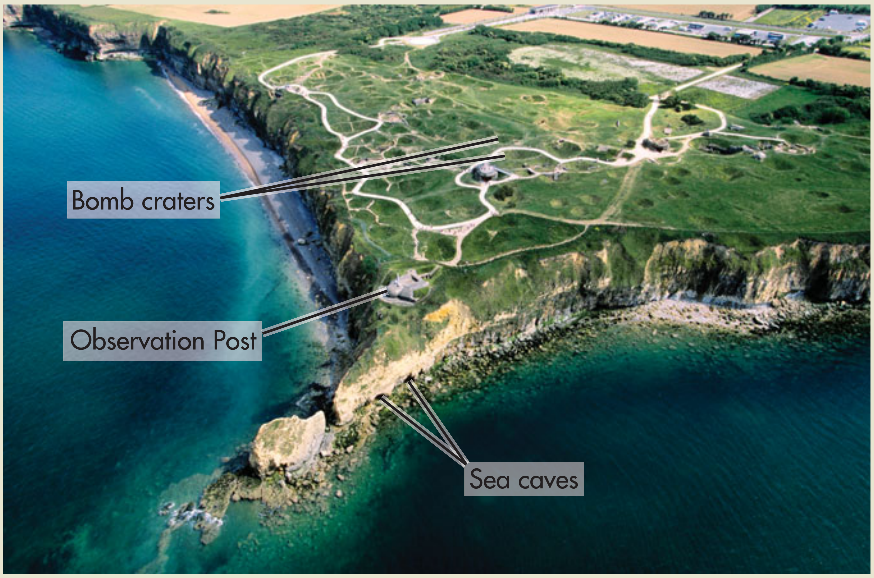
Coastal Erosion at Pointe du Hoc, France

Pointe du Hoc is located on the Normandy coast of France. It is located on a promontory point several hundred kilometers northwest of Paris, on the shore of the English Channel (**Figure 11.Ea**). The point is a historical site located on a coastal plain of low relief. The ocean side is a sea cliff, approximately 30 m high (Figure 11.Eb). Thousands of people visit the site annually to view the location where the invasion to free Europe in World War II began on June 6, 1944. Many consider the site to be so important that expending a large amount of money to preserve the most vulnerable parts of the point is worthwhile. Of course, this is a value judgment. The main problem is that the point has experienced as much as 10 m of erosion in the past 60 years. As a result, it was feared that the observation post might actually fall into the sea. Predictions were that it probably could not last more than a few decades, at most.

Those who want to preserve the last bit of rock on the point rather than, say, move some of the structures, obtained funding to evaluate whether the point might be preserved for another few decades if it were reinforced. This is an interesting approach to coastal erosion because it is a site-specific solution to a particular problem that involves coastal stabilization rather than, say, adjustment such as managed retreat. The case is also very interesting because it involves detailed geologic evaluation and study of processes of sea cliff retreat, linked to a specific strategy to reduce the rate of coastal erosion which has been estimated at 0.1 to 0.2 m per year.[9] Scientists and engineers studying the sea cliff realize that any attempt to absolutely stop sea cliff erosion is futile. Rather, their objective is a temporary solution to buy as much as 50 years. Total erosion in the past 60 years has been approximately 10 m (33 ft), and, in future decades, that rate might be significantly reduced.

The sea cliff was carefully evaluated and the geology studied in detail. The idealized profile of the

(a)



(b)

FIGURE 11.E Location of Pointe du Hoc (a) along the Normandy Coast of France; and (b) aerial image of the point. The historical site is on an elevated coastal plain underlain by Cretaceous limestone. Pits are World War II bomb craters. Note the small sea caves near the base of the sea cliff. *(Moirenc Camille/age fotostock)*

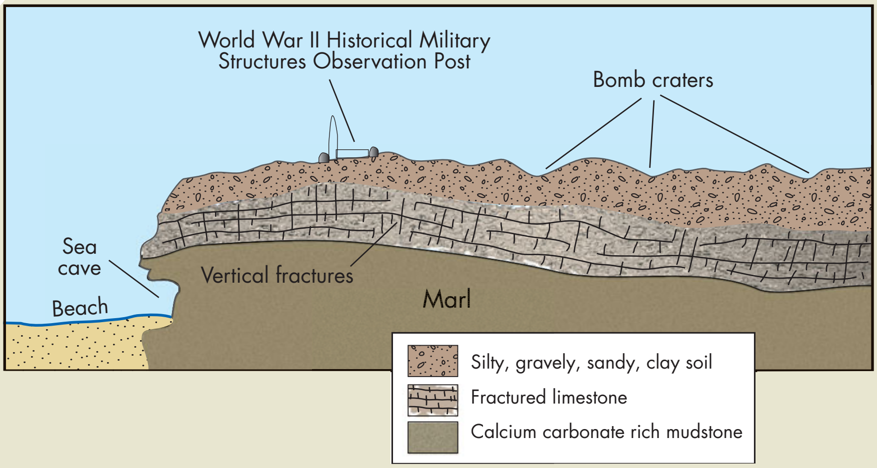


FIGURE 11.F Geology of Pointe du Hoc Near the Observation Post and sea cliff. *(Data from: J-L. Briand, et al. 2010. Pointe du Hoc Stabilization Report. Texas A&M University)*

sea cliff and the geology is shown in Figure 11.F. Three geologic layers are present:[9]

- The top layer, which is up to about 9 m thick, is a silty, gravelly, sandy, clay soil. This layer has relatively low strength and is prone to small landslides and grain-by-grain erosion resulting from precipitation.
- The middle layer is a fractured limestone that, with depth, becomes sandy and enriched with calcium carbonate muds. The layer is about 15 m thick. The limestone beds are nearly flat lying but have numerous nearly vertical fractures that are filled, to a lesser or greater extent, with weathered products of the limestone that are clay rich. Precipitation from the surface can remove some of the clay, resulting in the fractures being more open. The fractured limestone is vulnerable to larger slope failures, particularly if the rock is underlain by areas of coastal erosion that have produced wave-cut notches and sea caves. In fact, investigators studying the site have observed that this is the dominant failure mechanism that results in the most rock being lost from the sea cliff. When wave erosion undermines the rocks at the base, the rocks may fail along the fractures, falling onto the beach or into the sea.
- The lowest layer present is a black marl, which is a calcium carbonate–rich mudstone. Both the fractured limestone and the black marl have relatively high rock strength compared to the overlying soil.

A study of the sea cliff suggests that the attack of waves at the rock face near the beach dislodges blocks of rock and creates caverns, or sea caves. These are clearly visible along the base of the sea cliff and can be quite large, as illustrated in Figures 11.Ea, and 11.F. The caves grow larger and deeper with time and, eventually, leave the overlying rock unsupported; a failure may occur along fractures. It was concluded that the primary reason for collapse of the sea cliff is the presence of the caverns at the base of the cliff. As a result, the primary recommendation for reducing the rate of erosion is to fill the caverns and stabilize the base of the sea cliff. Work on this project began in 2010, and the objective is to fill the caverns with several hundred cubic meters of concrete. Rock bolts are also used to secure the concrete and stabilize the rocks. Following filling of the caverns, the outermost layer of cement is made to look like native rock. This is obviously a temporary solution because new sea caves can form, and the cement itself may be undermined and eroded. As a result, the study recommended a maintenance program based upon inspections and recognized that future work will undoubtedly be necessary. It is also important to recognize that the development of sea caves and large landslides is not the only process affecting the sea cliff. The top unit of the sea cliff is the weak soil, and numerous, small landslides are occurring on a regular basis. In fact, the top of the sea cliff has a wavy form, due to the many small landslides. Therefore, stabilizing the base of the sea cliff will not eliminate sea cliff retreat. It will probably reduce it by about one-half. Therefore, the work on the lower part of the sea cliff, which was completed in September 2010, will be a temporary solution at best. In the long run, the environmentally preferable solution will, by necessity, mean moving structures of historical importance back from the edge of the cliff. This is essentially the same solution reached in the case history at the beginning of the chapter, about the Cape Hatteras Lighthouse being moved inland.

In summary, the decision to use a "hard solution" to the sea cliff at Pointe du Hoc is an interesting one and is based on the value judgment

that the historical significance of the site is so great that measures need to be taken to preserve it. The cost of the work is modest to date, at about $6 million; however, future maintenance costs will be incurred, and, often, structures that are built in the sea cliff environment are fortified even more in subsequent years, so the total cost in the future is unknown. The solution to coastal erosion and the decision to minimize it at Pointe du Hoc is obviously a special circumstance, where a small length of sea cliff is stabilized. Should such an approach be applied to a long section of sea cliff, the cost would be far too great to maintain. For now, the point is better protected, and the erosion rate will probably decrease, but, in the future, if the site is to be maintained, important structures will need to be moved inland.

The Atlantic Coast

The Atlantic Coast from northern Florida to New York is characterized by *barrier islands*—long, narrow islands separated from the mainland by a body of water (**Figure 11.16**). Many barrier islands have been altered to some extent by human use and interest.

FIGURE 11.16 The Outer Banks The Outer Banks of North Carolina appear in this image from *Apollo 9* as a thin white ribbon of sand. The Barrier Islands are separated from the mainland by the Pamlico Sound. The brown color in the water is the result of sediment suspended in the water moving within the coastal system. Notice the fan-shaped plume of sediment just seaward of Ocracoke Inlet. The distance from Cape Lookout to Cape Hatteras is approximately 100 km (62 mi). *(NASA)*

The barrier island coast of Maryland illustrates some effects of human activity on coastal processes. Demand for the 50 km (30 mi) of Atlantic oceanfront beach in Maryland is very high, and the limited resource is used seasonally by residents of Washington, DC, and Baltimore, Maryland (**Figure 11.17**). Since the early 1970s, Ocean City on Fenwick Island has promoted high-rise condominium and hotel development on its waterfront. The natural frontal dune system of this narrow island has been removed in many locations, resulting in a serious beach erosion problem. Even more ominous is the almost certain possibility that a future hurricane will cause serious damage to Fenwick Island. The Ocean City inlet to the south of Ocean City formed during a hurricane in 1933. There is no guarantee, despite attempts to stabilize the inlet through coastal engineering, that a new inlet will not form, destroying, by erosion, part of Ocean City in the future.[11]

Assateague Island is located to the south, across the Ocean City inlet. It encompasses two-thirds of the Maryland coastline. In contrast to the highly urbanized Fenwick Island, Assateague Island is in a much more natural state. The island is used for passive recreation, such as sunbathing, swimming, walking, and wildlife observation. However, the two islands are in the same littoral cell, meaning they share the same sand supply. At least, that was the case until 1935, when the jetties were constructed

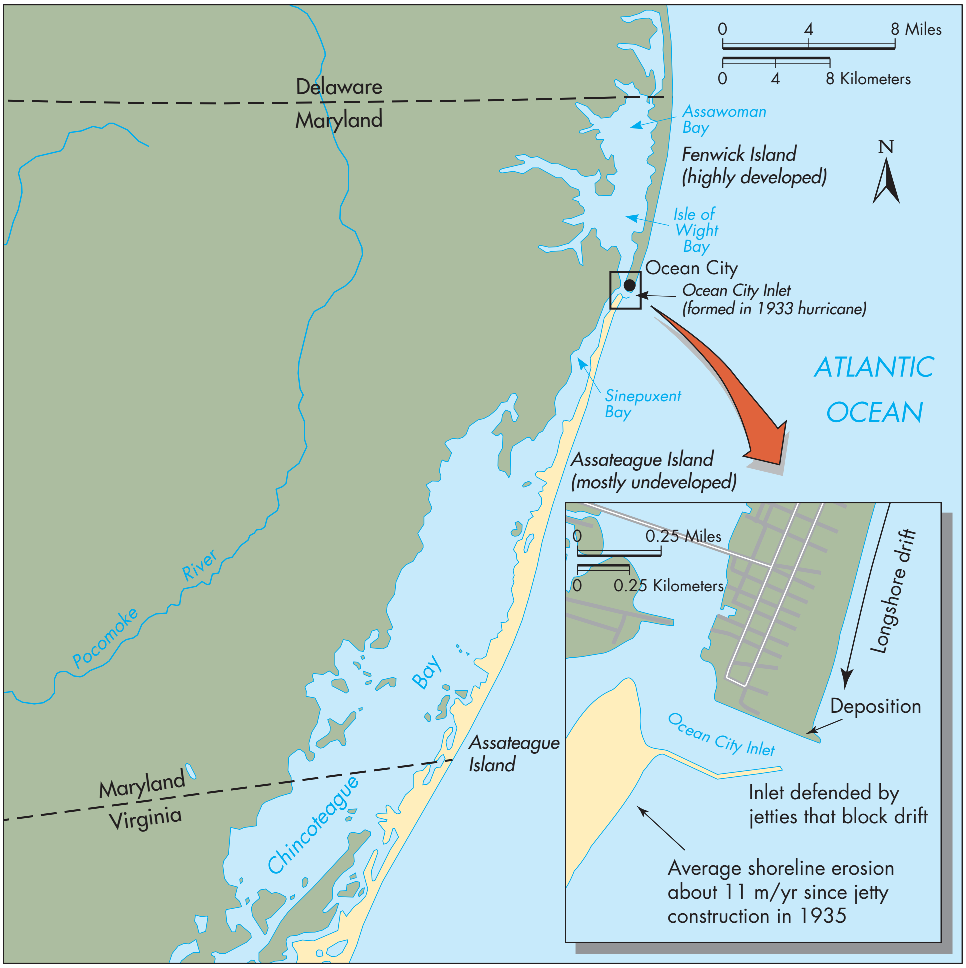


FIGURE 11.17 Urban development with jetty construction increases beach erosion The barrier island coast of Maryland. Fenwick Island is experiencing rapid urban development, and there is concern about potential hurricane damage. What will happen if a new inlet forms during a hurricane at the site of Ocean City? The inset shows details of the Ocean City inlet and effects of jetty construction.

to stabilize the Ocean City inlet. Since construction of the jetties, coastal erosion in the northern few kilometers of Assateague Island has averaged about 11 m (36 ft) per year, which is nearly 20 times the long-term rate of shoreline retreat for the Maryland coastline. During the same time, beaches immediately north of the inlet became considerably wider, requiring the lengthening of a recreational pier.[12]

Observed changes on Maryland's Atlantic coast are clearly related to the pattern of longshore drift of sand and human interference. Longshore drift is to the south at an average annual volume of about 150,000 m^3 (196,500 yd^3). Construction of the Ocean City inlet jetties interfered with the natural southward flow of sand and diverted it offshore rather than allowing it to continue southward to nourish the beaches on Assateague Island. Starved of sand, the northern portions of the island have experienced serious shoreline erosion during the past 50 years. This example of beach erosion associated with engineering structures that block longshore transport of sediment has been cited as the most severe that can be found in the United States.[12] Thus, the fundamental principle involving environmental unity holds: Earth is a system, a set of components that function together as a whole; a change in one part of the system affects all other parts.

The Gulf Coast

Coastal erosion is a serious problem along the Gulf of Mexico. One study in the Texas coastal zone suggests that, in the past 100 years, human modification of the coastal zone has accelerated coastal erosion by 30 to 40 percent over prehistoric rates.[13] The human modifications that appear to be most responsible for the accelerated erosion are

coastal engineering structures, subsidence as a result of groundwater and petroleum withdrawal, and damming of rivers that supply sand to the beaches.

The Great Lakes

Erosion is a periodic problem along the coasts of the Great Lakes and has been particularly troublesome along the Lake Michigan shoreline. Damage is most severe during prolonged periods of high lake levels that follow extended periods of above-normal precipitation. The relationship between precipitation and lake level has been documented since 1860 by the U.S. Army Corps of Engineers. The data show that the lake level has fluctuated about 2 m (6.6 ft) during this time. During a high-water stage, there is considerable coastal erosion, and many buildings, roads, retaining walls, and other structures are destroyed by wave erosion (**Figure 11.18**).[14] For example, in 1985, high lake levels due to fall storms caused an estimated $15 million to $20 million in damage.

During periods of below-average lake level, wide beaches develop that dissipate energy from storm waves and protect the shore. However, with rising lake-level conditions, the beaches become narrow, and storm waves exert considerable energy against coastal areas. Even a small lake-level rise on a gently sloping shore will inundate a surprisingly wide section of beach.[14]

Cliffs along the shores of lakes are referred to as *coastal bluffs* and are analogous to the sea cliffs of the ocean shoreline. Long-term rates of coastal bluff erosion at many Lake Michigan sites average about 0.4 m (1.3 ft) per year.[15] The severity of erosion at a particular site depends on many factors, including the following:

- Presence or absence of a frontal dune system. Dune-protected bluffs erode at a slower rate than unprotected bluffs.
- Orientation of the coastline. Sites exposed to high-energy storm winds and waves erode at an increased rate.
- Groundwater seepage. Seepage along the base of a coastal bluff causes slope instability, increasing the erosion rate.
- Existence of protective structures. Structures may be locally beneficial but often accelerate coastal erosion in adjacent areas.[14,15]

In recent years, beach nourishment has been attempted for some Great Lakes beaches. In some cases, sands that are coarser than the natural sands that had eroded have been added in the hope that the coarser, heavier sand will reduce the erosion potential.

FIGURE 11.18 Lakes have coastal erosion problems Coastal erosion along the shoreline of Lake Michigan has destroyed this home. *(Steve Leonard/Getty Images)*

11.6 Tropical Cyclones

Tropical cyclones are known as **typhoons** in most of the Pacific Ocean and **hurricanes** in the Atlantic. Tropical cyclones have taken hundreds of thousands of lives in a single storm. In November 1970, a tropical cyclone struck the northern Bay of Bengal in Bangladesh, producing a 6 m (20 ft) rise in the sea. Flooding caused by this sea-level rise killed approximately 300,000 people, caused $63 million in crop losses, and destroyed 65 percent of the total fishing capacity of the coastal region.[16] Another devastating cyclone hit Bangladesh in the spring of 1991, killing more than 100,000 people and causing more than $1 billion in damage. Hurricane Mitch, known as the deadliest Atlantic hurricane since 1780, was responsible for more than 11,000 deaths in Honduras and Nicaragua in 1998, and Hurricane Katrina in 2005 caused nearly 2,000 deaths, with damages of about $100 billion to New Orleans and other parts of the Gulf Coast (see Chapter 5).

Hurricane Form and Process

The origin for the word *hurricane* possibly comes from a Caribbean Indian word for "big wind" or "evil spirit." This certainly fits the bill! To be called a hurricane, a storm must have sustained winds of at least 119 km/hr (74 mph). Hurricanes are a variation of the tropical cyclone, which is the general term for a huge, complex series of thunderstorms that rotate around an area of low pressure, forming over warm, tropical ocean water.

Hurricanes begin as tropical disturbances, which are large areas of unsettled weather with a diameter as large as 600 km (370 mi). Within this area, there exists an organized mass of thunderstorms with a general low pressure in which there is initial rotation caused by the movement of the storm and rotation of Earth. A tropical depression may grow in size and strength as warm, moist air is drawn into the depression and begins to rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The process that increases the intensity of the storm is caused by warm water that evaporates from the sea and is drawn into the storm. As this process occurs, the energy of the storm increases. As warm seawater evaporates, it is transformed from liquid water in the sea to water vapor (gas) in the air mass of the storm. When this happens, potential energy in the form of *latent heat* enters the storm. Latent heat of water is the amount of heat required to change liquid water to water vapor. Latent heat is one of the major sources of the power (time rate of energy expenditure) of a hurricane. As the moist air rises, condensation (rain) occurs as the latent heat is released, warming the air and making it lighter. As the lighter air rises, more energy from warm water is drawn in, and the storm may increase in size, strength, and intensity. If wind speeds in the storm reach 63 km (39 mi), the depression is called a *tropical storm* and receives a name.

Hurricanes are very high-energy storms. Their size can be huge by human standards. It is not unusual to observe on satellite images a hurricane moving toward the United States that has an area nearly the size of the Gulf of Mexico, stretching from Florida to Texas and beyond.

A generalized diagram of a hurricane and the processes that occur within it are shown in **Figure 11.19**. The hurricane has bands of spinning storms and thunder cells with an eye where air is subsiding in the center around what is called the eye wall. As the moist air rotates within the storm, intense rain bands are produced. When a hurricane moves across the land (mainland or island), it is deprived of some of its energy and often weakens. When a hurricane makes landfall on a continent and moves inland, it weakens and eventually dies, but the storm and rainfall can cause serious river flooding well inland. The intense rainfall on slopes may generate numerous landslides, producing an additional hazard.

Hurricanes are classified based upon their size and intensity. **Table 11.1** (page 390) is the Saffir-Simpson Hurricane Scale. It is used to estimate potential wind damage and flooding. There are five categories, with Category One being the smallest and Category Five the largest. Category Five hurricanes are capable of producing catastrophic damage, but even a Category One storm is a very serious and dangerous event.

We know when a hurricane is coming. Images from satellites and high-altitude aerial photographs show the locations of tropical depressions and tropical storms that we may monitor to see if they will

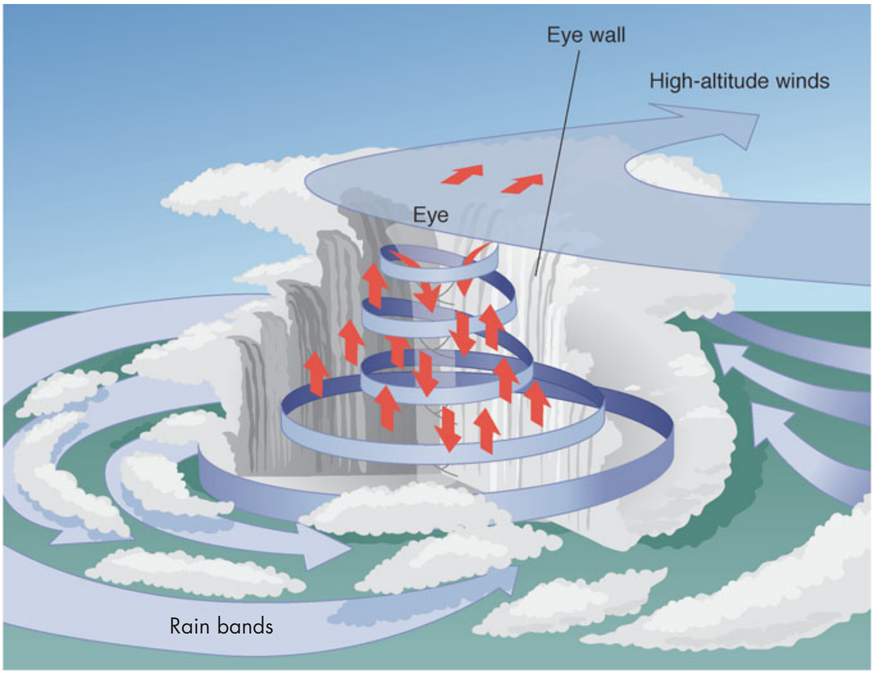


FIGURE 11.19 Hurricane form and process Energy from warm ocean water is transformed into the storm, which may have a diameter of 600 km (370 mi). Main components are rotating bands of thunderstorms; rising warm air around an eye of clear sky with subsiding air; and the eye wall as the boundary between the rotating rain bands and eye.

become hurricanes. In order to verify satellite data, special airplanes are flown through storms to record wind speed, air temperature, and air pressure. Once a hurricane has formed, its continual movement (called its *path*) is monitored. The paths of four hurricanes in 2005 are shown in **Figure 11.20** (page 391).

As hurricanes get close to landfall, moving over shallower water, they generally slow down. However, if they encounter warmer water, they may actually increase in intensity.

The most dangerous aspect of hurricanes is not the wind itself, although violent winds can be lethal. Often, what causes the most flooding and loss of life is the **storm surge**, which arrives with the storm (**Figure 11.21**, page 391). The storm surge is a local rise in sea level that results when hurricane winds push water toward the coast. Storm surges may arrive as a quick rise in sea level or a series of waves that may increase water depths near the coast by several meters to more than 10 m (30 ft). Storm surge is generally highest on the part of the rotating storm that pushes landward. For example, along the Gulf Coast, the storm surge and wind speed are higher to the east than west (i.e., the right front quadrant of the storm) as the hurricane rotates in a counterclockwise direction. During Hurricane Katrina (see the opening case in Chapter 5), the storm surge east of New Orleans was significantly higher than in the central and western parts of the storm. If a storm arrives coincidentally with a high tide, a storm surge of even greater height occurs. Most of the deaths from hurricanes are caused by storm surges as people are drowned or struck by solid objects within the surge. When the surge moves ashore, it is not a tall advancing line of water but is more like a continual increase in rise of sea level as the hurricane approaches and makes landfall. Having said this, the actual storm surge in places may well appear as a series of wavelike forms that inundate the land.

Most hurricanes and typhoons form in a belt between 8 degrees north and 15 degrees south of the equator, where warm surface-water temperatures exceed about 27°C (80°F). During an average year, approximately five hurricanes will develop that might threaten the Atlantic and Gulf Coasts.

TABLE 11.1 The Saffir-Simpson Hurricane Scale

The Saffir-Simpson Hurricane Scale assigns a 1 to 5 rating based on the hurricane's present intensity. This rating gives an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf in the landfall region, where the hurricane is expected to come on land.

Category One Hurricane	Winds 119 to 153 km/hr (74–95 mph). Storm surge generally 1.2 to 1.5 m (4 to 5 ft) above normal. No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Also, some coastal road flooding and minor pier damage. Hurricanes Allison of 1995 and Danny of 1997 were Category One hurricanes at peak intensity.
Category Two Hurricane	Winds 154 to 177 km/hr (96 to 110 mph). Storm surge generally 1.8 to 2.4 m (6 to 8 ft) above normal. Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees, with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2 to 4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings. Hurricane Bonnie of 1998 was a Category Two Hurricane when it hit the North Carolina coast; Hurricane George of 1998 was a Category Two hurricane when it hit the Florida Keys and the Mississippi Gulf Coast.
Category Three Hurricane	Winds 178 to 209 km/hr (111 to 130 mph). Storm surge generally 2.7 to 3.7 m (9 to 12 ft) above normal. Some structural damage to small residences and utility buildings, with a minor amount of wall failures. Damage to shrubbery and trees, with foliage blown off trees and large trees blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut off by rising water 3 to 5 hours before arrival of the hurricane center. Flooding near the coast destroys smaller structures, and larger structures are damaged by battering by floating debris. Terrain continuously lower than 1.5 m (5 ft) above mean sea level may be flooded inland 13 km (8 mi) or more. Evacuation of low-lying residences within several blocks of the shoreline may be required. Hurricane Roxanne of 1995 was a Category Three hurricane at landfall on the Yucatan Peninsula of Mexico; Hurricane Fran of 1996 was a Category Three hurricane at landfall in North Carolina.
Category Four Hurricane	Winds 210 to 249 km/hr (131 to 155 mph). Storm surge generally 4 to 5.5 m (13 to 18 ft) above normal. More extensive wall failures, with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 3.1 m (10 ft) above sea level may be flooded, requiring massive evacuation of residential areas as far inland as 10 km (6 mi). Hurricane Luis of 1995 was a Category Four hurricane while moving over the Leeward Islands; Hurricanes Felix and Opal of 1995 also reached Category Four at peak intensity. Hurricane Katrina (2005) was Category Four at landfall.
Category Five Hurricane	Winds greater than 249 km/hr (155 mph). Storm surge generally greater than 5.5 m (18 ft) above normal. Complete roof failure on many residences and industrial buildings. Some complete building failures, with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 4.6 m (15 ft) above sea level and within 458 m (500 yd) of the shoreline. Massive evacuation of residential areas on low ground within 8 to 16 km (5 to 10 mi) of the shore line may be required. Hurricane Mitch of 1998 was a Category Five hurricane at peak intensity over the western Caribbean. Hurricane Gilbert of 1988 was a Category Five hurricane at peak intensity and was one of the strongest Atlantic tropical cyclones of record.

Modified after Spindler, T., and Beven, J. 1999. Saffir-Simpson Hurricane Center, National Oceanic and Atmospheric Administration. www.nhc.noaa.gov.aboutsshs.html. Accessed 5/23/01.

One of three likely storm tracks may develop (**Figure 11.22**, page 392):

1. A storm heads toward the east coast of Florida, sometimes passing over islands such as Puerto Rico, and then, before striking the land, it moves out into the Atlantic to the northeast.
2. A storm travels over Cuba and into the Gulf of Mexico to strike the Gulf Coast.
3. A storm skirts along the East Coast and may strike land from central Florida to New York.

Storms that may develop into hurricanes are closely monitored from both satellites and specially designed aircraft that fly through the storms.

FIGURE 11.20 Paths of four hurricanes in 2005 *(National Hurricane Center)*

FIGURE 11.21 Storm surge and high waves The storm surge shown here was produced by Hurricane Gloria on September 27, 1985, in New Jersey. *(Scott Thode/Image State)*

Hazards presented by hurricanes include high winds that may rip shingles and rafters from roofs, blow over large trees and utility lines, and generally wreak havoc on structures built by people. The processes that kill most people and often cause the most damage, however, are flooding resulting from intense precipitation and landward transport of wind-driven waves of ocean waters and, as previously mentioned, storm surges.[17]

The probability that a hurricane will strike a particular 80 km (50 mi) coastal segment of the Atlantic or Gulf Coast in a given year is shown in **Figure 11.23**. Notice that the probabilities are particularly high in southern Florida and on the Louisiana coastline.

Property damage from hurricanes can be staggering, as in the case of Hurricane Katrina. As another example, consider Hurricane Andrew, which struck Florida in August 1992. The storm was one of the costliest storms in U.S. history, with estimated damages in excess of $25 billion. Despite evacuation, 23 lives were lost as a direct result of the storm, and 250,000 people were temporarily rendered homeless. Damages to homes and other buildings were extensive: About 25,000 homes were destroyed as entire neighborhoods in Florida were flattened (**Figure 11.24**).[18] More than 100,000 buildings were damaged, including the National Hurricane Center in Florida, where a radar antenna housed in a protective dome was torn from the roof.[18] Two hurricanes in the summer of 1996 struck the North Carolina coast. The second storm in August caused about $3 billion in property damage and killed more than 20 people.

FIGURE 11.22 Hurricane paths Three common paths of hurricanes in the Atlantic.

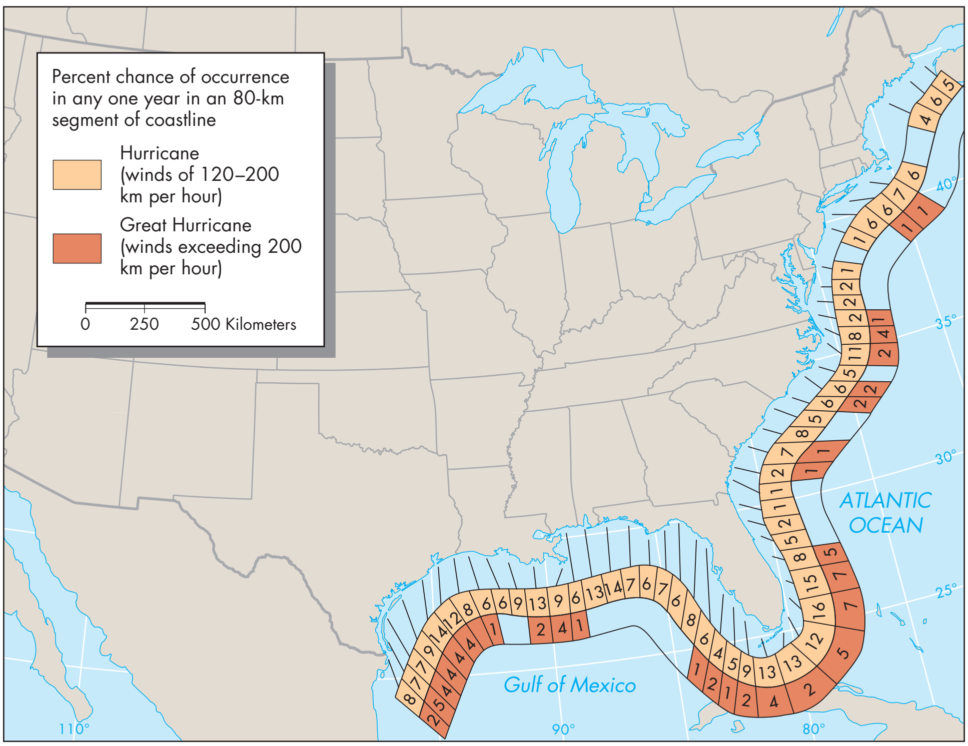
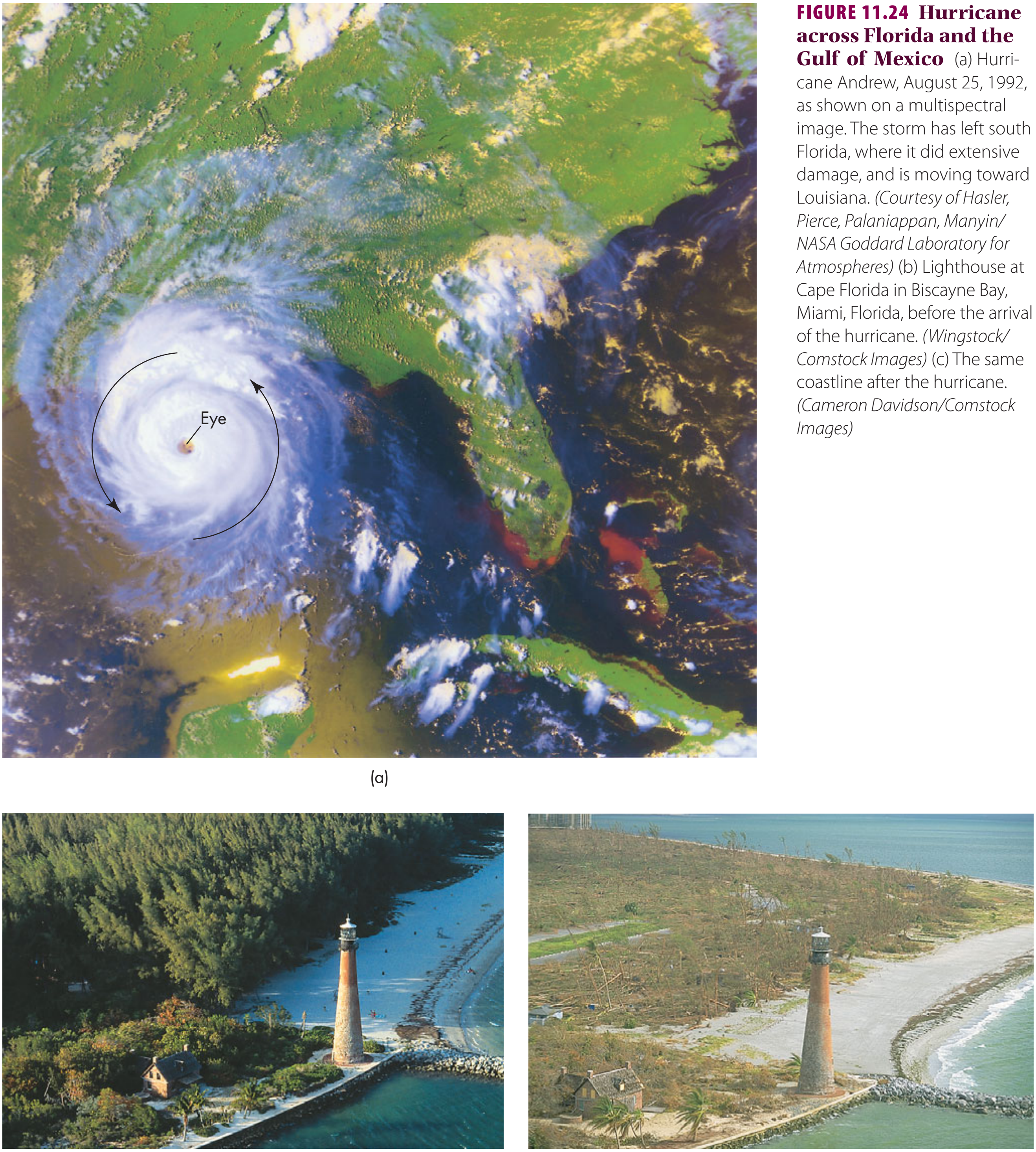


FIGURE 11.23 Hurricane hazard map Probability that a hurricane will strike a particular 80 km (50 mi) south Atlantic coastal segment in a given year. *(From Council on Environmental Quality, 1981. Environmental trends)*



(a)

(b)

(c)

FIGURE 11.24 Hurricane across Florida and the Gulf of Mexico (a) Hurricane Andrew, August 25, 1992, as shown on a multispectral image. The storm has left south Florida, where it did extensive damage, and is moving toward Louisiana. *(Courtesy of Hasler, Pierce, Palaniappan, Manyin/ NASA Goddard Laboratory for Atmospheres)* (b) Lighthouse at Cape Florida in Biscayne Bay, Miami, Florida, before the arrival of the hurricane. *(Wingstock/ Comstock Images)* (c) The same coastline after the hurricane. *(Cameron Davidson/Comstock Images)*

Although the population has increased along the Atlantic and Gulf Coasts, the loss of lives from hurricanes has decreased significantly because of more effective detection and warning. The amount of property damage, however, has greatly increased.

There is concern for large cities such as Miami and New Orleans (especially after experiencing Katrina in 2005). Unsatisfactory evacuation routes, building codes, and disaster preparedness may contribute to another catastrophic hurricane along the Atlantic or Gulf Coast.

11.7 Perception of and Adjustment to Coastal Hazards

Perception of Coastal Erosion

An individual's past experience, proximity to the coastline, and probability of suffering property damage all play primary roles in the perception of coastal erosion as a natural hazard. One study of coastal erosion of sea cliffs near Bolinas, California, 24 km (15 mi) north of the entrance to the San Francisco Bay, established that people living close to the coast in an area likely to experience damage in the near future are generally very well informed and see the erosion as a direct and serious threat.[16,19] People living a few hundred meters from a possible hazard, although aware of the hazard, know little about its frequency of occurrence, severity, and predictability. Still farther inland, people are aware that coastal erosion exists but have little perception of it as a hazard.

Adjustment to Coastal Hazards

Tropical Cyclones. People adjust to the tropical cyclone hazard either by doing nothing and bearing the loss or by taking some kind of action to modify potential loss. For example, homes in hurricane-prone areas may be constructed to allow the storm surge to pass under the house (**Figure 11.25**). Community adjustments include attempts to modify potential loss by strengthening the environment with protective structures and land stabilization and by adapting better land use zoning, evacuation procedures, and warning procedures. [20] Some general guidelines of what to do before, during, and after a hurricane are listed in **Table 11.2**.

Coastal Erosion. Adjustments to coastal erosion generally fall into one of three categories:

- Beach nourishment that tends to imitate natural processes, the "soft solution"
- Shoreline stabilization through structures such as groins and sea walls, the "hard" solution
- Land use change that attempts to avoid the problem by not building in hazardous areas or by relocating threatened buildings

A preliminary process in any approach to managing coastal erosion is estimating the rates of erosion. Estimates of future erosion rates are based on historical shoreline change or statistical analysis of the oceanographic environment, such as the waves, wind, and sediment supply that affect coastal erosion. Recommendations are then made concerning setbacks considered to be minimum standards for state or local coastal erosion management programs. A setback is the distance from the shoreline to where development, such as homes, is allowed. A small number of states (including Florida, New Jersey, New York, and North Carolina) use a setback distance for buildings based on the rate of erosion (see A Closer Look: E-Lines and E-Zones).[21] The concept of setback has merit in coastal erosion man-

FIGURE 11.25 Hurricane-resistant house Home in the Florida Keys, constructed with strong blocks to withstand hurricane-force wind and space below to allow the flow of a storm surge beneath the building. *(Edward A. Keller)*

TABLE 11.2 What to Do Before, During, and After a Hurricane

Before a Hurricane	• Probably the most important thing you can do before a hurricane is to plan your evacuation route. The plan should include information concerning the safest evacuation route as well as locations of nearby shelters. Be prepared to drive inland to a safe place 13 to 31 km (20 to 50 mi).
	• Prepare a disaster kit, including a flashlight with extra batteries, a portable battery-operated radio, a first-aid kit, emergency food and water, a can opener, necessary medicines, cash and credit cards, and a change of clothes, including sturdy shoes.
	• Make arrangements to care for your pets. Pets may not be allowed in emergency shelters.
	• Have a family plan on how to respond after a hurricane and be sure that members of the family know how to turn off household gas, electricity, and water.
	• Teach young children when and how to call for emergency assistance from police or fire departments and which radio stations to listen to for emergency information.
	• Protect your windows with permanent shutters or be prepared to use plywood panels cut to fit each window. It is important to put up window protection long before the storm arrives.
	• Homeowner insurance policies do not cover damage from flooding that accompanies a hurricane, so obtain flood insurance.
	• Develop a family emergency communication plan. Family members may be separated during a disaster. Your plan should include how you are going to get back together.
	• Ask an out-of-state relative or friend to serve as your family contact. After a hurricane, it is often easier to call long distance than within your area. Be sure everyone in your family knows the name, address, and phone number of the family contact.
	• Hurricanes are generally spotted far out at sea days before they strike land. A hurricane watch is issued when there is a threat that hurricane conditions will occur within 24 to 36 hours. A hurricane warning is issued when hurricane conditions are expected in 24 hours or less.
During a Hurricane Watch	• Listen to your television or radio for hurricane progress reports.
	• Check emergency supplies.
	• Be sure there is fuel in your car.
	• Bring inside outdoor objects such as lawn furniture, toys, and garden tools. Objects that cannot be brought inside should be anchored.
	• Secure your home and other buildings by closing and boarding up windows.
	• Remove outside antennas or satellite dishes.
	• Because power outages are likely during a storm, turn your refrigerator and freezer to the coldest possible settings and open them only when absolutely necessary.
	• Store drinking water in clean bathtubs, bottles, and cooking utensils.
	• Review with your family your evacuation plan.
	• If you have a boat, be sure it is secure or moved to a designated safe place.

(*continued*)

TABLE 11.2 What to Do Before, During, and After a Hurricane (*continued*)

During a Hurricane Warning	• Listen constantly to television or radio for official instructions.
	• If you live in a mobile home, check your tiedowns and evacuate immediately.
	• Store your valuables and personal papers in waterproof containers in the highest level of your home.
	• Avoid elevators.
	• Stay inside and away from windows, skylights, and glass doors.
	• Keep a supply of flashlights and extra batteries on hand. Avoid using open flames such as candles or kerosene lamps.
	• If electrical power is lost, turn off major appliances to reduce power surges when electricity is restored.
	• If officials indicate that evacuation is necessary, leave as soon as possible, avoiding flooded roads and washed-out bridges. Secure your home by unplugging appliances and turning off electricity and the main water valve. Let someone outside the storm area know where you are going. If time permits, move furniture to protect it from flooding; if possible, move it to a higher floor. Load preassembled emergency supplies and warm protective clothing, including sleeping bags and blankets. Finally, lock up your home and leave!
After a Hurricane	• Stay tuned to local radio and television for information.
	• Assist injured or trapped persons. Do not move seriously injured persons unless they are in immediate danger. Call for help.
	• Return to your home only after authorities have advised you that it is safe to do so.
	• When you return home, be aware of the possibility of dangling power lines and enter your home with caution. Be aware of snakes, insects, and animals that may have been driven to higher ground by floodwaters. Open your windows and doors to ventilate and dry your home. Check your refrigerator for foods that may have spoiled. Finally, take pictures of the damage to both the house and its contents for insurance purposes.

Modified after Federal Emergency Management Agency. *Fact Sheet: Hurricanes*. www.fema.gov/library/hurricaf.htm. Accessed 5/10/2001.

agement and is at the heart of land use planning to minimize damage from coastal erosion.

We are at a crossroads today with respect to adjustment to coastal erosion. One road leads to ever-increasing coastal defenses in an attempt to control the processes of erosion. The second road involves learning to live with coastal erosion through flexible environmental planning and wise land use in the coastal zone.[22,23] The first road follows history in our attempt to control coastal erosion through the construction of engineering structures, such as seawalls. In the second road, structures in the coastal zone, with such exceptions as critical facilities in certain areas, are considered temporary and expendable. Development in the coastal zone must be in the best interests of the general public rather than for a few who profit from developing the oceanfront. This philosophy is at odds with the viewpoint of developers, who consider the coastal zone too valuable not to develop. In fact, development in the coastal zone is not the problem; rather, the problem lies in the inappropriate development of hazardous areas and areas better suited for uses other than building. In other words, beaches belong to all people to enjoy, not only to those fortunate enough to purchase beachfront property. The state of Hawaii has taken this idea to heart: There, all beaches are public property, and local property owners cannot deny access to others.

Accepting the philosophy that, with minor exceptions, coastal zone development is temporary and expendable and that consideration should first be to the general public requires an appreciation of the following five principles:[22]

1. Coastal erosion is a natural process rather than a natural hazard; erosion problems occur when people build structures in the coastal zone. The coastal zone is an area where natural processes associated with waves and moving sediment occur. Because such an environment

A Closer Look

E-Lines and E-Zones

Recently, a special committee of the National Research Council (NRC), at the request of the Federal Emergency Management Agency (FEMA), developed coastal zone management recommendations, some of which follow:[21]

- Future erosion rates should be estimated on the basis of historical shore line change or statistical analysis of the oceanographic environment (i.e., the waves, wind, and sediment supply that affect coastal erosion).
- E-lines and E-zones based on erosion rates should be mapped (**Figure 11.G**). The *E* stands for *erosion*; for example, the E-10 line is the location of expected erosion in 10 years. The E-10 zone is considered to be an imminent hazard where no new habitable structures should be allowed. The setback distance depends on the erosion rate. For example, if the rate is 1 m (3.3 ft) per year, the E-10 setback is 10 m (33 ft).
- Movable structures are allowed in the intermediate and long-term hazard zones (E-10 to E-60) (see Figure 11.G).
- Permanent large structures are allowed at setbacks greater than the E-60 line.
- New structures built seaward of the E-60 line, with the exception of those on high bluffs or sea cliffs, should be constructed on pilings to withstand erosion associated with a high-magnitude storm with a recurrence interval of 100 years.

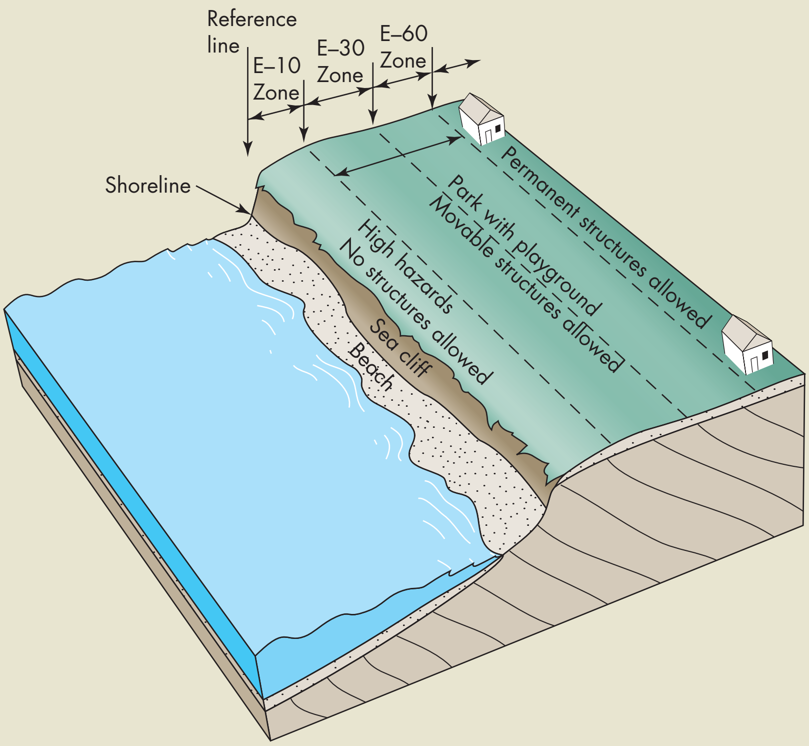


FIGURE 11.G Erosion hazard zones Idealized diagram illustrating the concept of the E-lines and E-zones based on the rate of coastal erosion from a reference point such as the sea cliff or dune line. The width of the zone depends on the rate of erosion and defines a setback distance. Of course, even with setbacks based on 60 years of expected erosion (E-60 line), eventually, 60 years down the road, structures will be much closer to the shoreline and will become vulnerable to erosion. It is a form of planned obsolescence. *(From National Research Council. 1990. Managing Coastal Erosion. Washington, DC: National Academy Press)*

NRC recommendations concerning setbacks are considered to be minimum standards for state or local coastal erosion management programs. A small number of states (including Florida, New Jersey, New York, and North Carolina) use a setback based on the rate of erosion; however, most states do not require this type of setback. Nevertheless, the concept of E-lines and E-zones based on erosion-designated setbacks and allowable construction has real merit in coastal zone management.

will have a certain amount of natural erosion, the best land uses are those compatible with change. These include recreational activities such as swimming and fishing.

2. Any shoreline construction causes change. The beach environment is dynamic. Any interference with natural processes produces a variety of secondary and tertiary changes, many of which may have adverse consequences. Adverse consequences are particularly likely when engineering structures, such as groins and sea walls that affect the storage and flow of sediment along a coastal area, are used.
3. Stabilization of the coastal zone through engineering structures protects the property of relatively few people at a large expense to the general public. Engineering structures along the shoreline are often meant to protect developed property, not the beach itself. It has been argued that the interests of people who own shoreline property are not compatible with the public interest and that it is unwise to expend large amounts of public funds to protect the property of a few.
4. Engineering structures designed to protect a beach may eventually destroy it. Engineering structures often modify the coastal environment to such an extent that it may scarcely resemble a beach. For example, construction of large sea walls causes reflection of waves and turbulence that eventually narrow the beach.
5. Once constructed, shoreline engineering structures produce a trend in coastal development that is difficult, if not impossible, to reverse. Engineering structures often lead to additional repairs and larger structures, with spiraling costs. In some areas, the cost of the structures eventually exceeds the value of the beach property itself. For these and other reasons, several states have recently imposed severe limitations on future engineering construction intended to stabilize the coastline. As sea levels continue to rise and coastal erosion becomes more widespread, the nonstructural alternatives to the problem should continue to receive favorable attention because of both financial necessity and the recognition that the amenities of the coastal zone should be kept intact for future generations to enjoy.

If you consider purchasing land in the coastal zone, remember these guidelines:[23] (1) Allow for a good setback from the beach or sea cliff; (2) be high enough above sea level to avoid flooding; (3) construct buildings to withstand adverse weather, especially high winds; and (4) if hurricanes are a possibility, be sure there are adequate evacuation routes. Remember, it is always risky to buy property where land meets water.

Making The Connection

Linking the Opening Case History About Moving the Lighthouses to the Fundamental Concepts

Consider and discuss the following questions:

1. What are potential links between human population, land use, and coastal planning that go into the process of deciding whether to move a structure from the coastal erosion hazard zone or to defend it where it is?
2. How does moving a lighthouse relate to sustainable coastlines? Start by defining what a sustainable coastline might be.
3. What are the scientific questions concerning possibly moving the Montauk Lighthouse on Long Island? What are the values that might be considered?
4. How do value judgments enter into the decision of moving or not moving structures vulnerable to erosion back from harms way?

Summary

The coastal environment is one of the most dynamic areas on Earth, and rapid change is a regular occurrence. Migration of people to coastal areas is a continuing trend, and approximately 75 percent of the population in the United States now live in coastal states.

Ocean waves are generated by storms at sea and expend their energy on the shoreline. Irregularities in the shoreline account for local differences in wave erosion; these irregularities are largely responsible for determining the shape of the coast. Beaches are most commonly formed by accumulations of sand or gravel that are deposited at the coast by rivers and shaped by wave action. Actually, beaches can form from any loose material, such as broken shells or coral or volcanic rock, located in the shore zone. Waves striking a beach at an angle result in longshore transport of the beach sediments.

Rip currents are a serious hazard to swimmers, killing up to 200 people a year in the United States. They can be recognized and avoided, and it is possible to escape from them if you do not panic.

Although coastal erosion causes a relatively small amount of property damage compared with other natural hazards, such as river flooding, earthquakes, and tropical cyclones, it is a serious problem along all the coasts of the United States, including the shorelines of the Great Lakes. Factors contributing to coastal erosion include river damming, high-magnitude storms, and the worldwide rise in sea level.

Human interference with natural coastal processes, such as the building of sea walls, groins, breakwaters, and jetties, is occasionally successful, but in many cases, it has caused considerable coastal erosion. Sand tends to accumulate on the updrift side of the structure and erode on the downdrift side. Most problems occur in areas with high population density, but sparsely populated areas along the Outer Banks in North Carolina are also experiencing trouble with coastal erosion. Beach nourishment has had limited success in restoring or widening beaches, but it remains to be seen whether it will be effective in the long term.

The most catastrophic coastal hazard is the tropical cyclone. Also called typhoons and hurricanes, tropical cyclones are violent storms that bring high winds, storm surges, and river flooding. They continue to take thousands of lives and to cause billions of dollars in property damage.

Perception of the coastal erosion hazard depends mainly on the individual's experience with and proximity to the hazard. Community and individual adjustments to tropical cyclones generally attempt to modify the environment by building protective structures designed to lessen potential damage or to encourage change in people's behavior by better land use zoning, evacuation, and warning.

Adjustment to coastal erosion in developed areas is often the "technological fix": building sea walls, groins, and other structures or (more recently) using beach nourishment. These approaches to stabilizing beaches have had mixed success and may cause additional problems in adjacent areas. Engineering structures are very expensive, require maintenance, and, once in place, are difficult to remove. The cost of engineering structures may eventually exceed the value of the properties they protect; such structures may even destroy the beaches they were intended to save. Managing coastal erosion will benefit from careful land use planning that emphasizes establishment of designated setbacks and allowable construction determined by predicted rates of coastal erosion.

Revisiting Fundamental Concepts

Human Population Growth Many populated areas are located near the coast, and human population in the coastal zone is expected to continue to increase. As a result, potential impacts of coastal hazards will increase.

Sustainability Coastal areas contain some of the most scenic and valuable property on Earth. In order to maintain a quality environment in the coastal zone, we must develop plans to sustain our coast for future generations. Sustaining the coast will involve learning to live with and adjust to coastal hazards through land use planning that maintains the integrity of the coastal environment.

Earth as a System Coastal environments are complex systems where rapid change is often the norm. Learning to live with change in the coastal environment is a necessity.

Hazardous Earth Processes, Risk Assessment, and Perception The most hazardous processes in the coastal environment are coastal erosion and flooding associated with tropical cyclones. The impacts of these hazards are increasing as a result of increased development in the coastal zone and global climate change, which is causing a rise in sea level. In general, people living in the coastal zone are aware of potential

hazards, and there have been many studies in coastal areas to evaluate risk and to recommend appropriate adjustments so that loss of life and property may be minimized.

Scientific Knowledge and Values It is clear that people value the coastal environment. Scientific knowledge concerning coastal processes is a mature field of study, and, in general, we know where hazards are most likely to occur and what their potential impacts are. Solutions to reducing coastal hazards vary from building hard engineering structures to reduce damage to softer approaches that allow us to live in the coastal zone and adjust to hazards. The solution we choose for a particular site depends in part upon how we value the coastal zone. For example, if a row of beach homes is being threatened by erosion, the choices may be building a sea wall, which would eventually cause the loss of the beach, or moving the homes inland, out of harm's way.

Key Terms

beach (p. 369)
beach budget (p. 372)
beach nourishment (p. 378)
breakwater (p. 379)
groin (p. 378)
hurricane (p. 388)
jetty (p. 380)
longshore sediment transport (p. 370)
rip current (p. 371)
sea cliff (p. 374)
sea wall (p. 378)
storm surge (p. 389)
tropical cyclone (p. 388)
typhoon (p. 388)

Review Questions

1. How does wave refraction at a rocky point result in concentration of wave energy at the point?
2. What is the difference between plunging and spilling breakers?
3. What are the processes of longshore transport of sand?
4. What are some of the human activities that can increase sea cliff erosion?
5. What are some of the important differences in coastal processes and beach erosion between the East and West Coasts of the United States?
6. What are the major alternatives to stabilize a coast? Which is preferred in a particular situation? Why?
7. What are sea walls and groins, and why are they constructed? What is their effect on erosion and coastal processes?
8. What are the processes important in the formation of a hurricane?
9. What is the process of beach nourishment, and what is its objective?
10. What are the major factors causing erosion problems for the Great Lakes?
11. What is storm surge, and how is it produced?
12. What are the three major adjustments to coastal erosion?
13. What are the five general principles that should be accepted if we choose to live with, rather than control, coastal erosion?

Critical Thinking Questions

1. Do you think that human activity has increased the coastal erosion problem? Outline a research program that could test your hypothesis.
2. Do you agree or disagree with the statements that all structures in the coastal zone (with the exceptions of critical facilities) should be considered temporary and expendable and that any development in the coastal zone must be in the best interest of the general public rather than the few who developed the oceanfront? Explain your position.
3. A beach park is experiencing coastal erosion. Some want to protect the park, including a restaurant, parking lots, an outhouse, and a lawn at any cost; they don't want to lose a blade of grass. That would require a hard solution, such as a sea wall. Others want to maintain the sand beach and use a more flexible approach to the erosion. They argue for beach nourishment and planned retreat. Both groups have clearly stated their values. What are the pros and cons for each position? Can the two views be considered simultaneously?

Companion Website

www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Siberian impact 1908 Tunguska event (artist image) just prior to the atmospheric 10-megaton (equivalent to TNT) blast and destruction of a 30 m-diameter asteroid several kilometers above Siberia. The blast flattened and burned over 2,000 km^2 (770 mi^2) of forest but left no crater. *(Joe Tucciarone)*

12 Impact of Extraterrestrial Objects

Written with the assistance of Frank Spera

Learning Objectives

Bombardment of Earth by objects from space has been occurring since the birth of our planet. Such impacts have been linked to the extinction of many species, including the dinosaurs. The risk of impact from asteroids, comets, and meteoroids continues today. Learning objectives for this chapter include:

- **Know the difference between asteroids, meteoroids, and comets**
- **Understand the physical processes associated with aerial burst and impact craters**
- **Understand the possible causes of mass extinction**
- **Know the evidence for the impact hypothesis of the cause of the late Cretaceous mass extinction**
- **Know the evidence for the impact hypothesis of the cause of the extinction of the late Pleistocene (Younger Dryas) megafauna about 12,900 years ago**
- **Know the likely physical, chemical, and biological consequences of impact from a large asteroid or comet**
- **Understand the risk of impact or aerial burst of extraterrestrial objects and how that risk might be minimized**

Case History

The Tunguska Event

On June 30, 1908, shortly after 7 A.M., witnesses in Siberia reported observing a blue-white fireball with a glowing tail descending from the sky. The fireball exploded above the Tunguska River Valley in a heavily forested, sparsely populated area. Later, calculations would show that the explosion had the force of 10 megatons of TNT, equivalent to 10 hydrogen bombs. Though there were few witnesses close to the event, the sounds from the explosion were heard hundreds of kilometers away, and the blast wave was recorded at meteorological recording sites throughout Europe. The tremendous air blast caused more than 2,000 km^2 (770 mi^2) of forest to be flattened and burned (**Figure 12.1**).

A herdsman in the vicinity of the blast was one of the few people who witnessed the devastation on the ground. His hut was completely flattened by the blast, and its roof was blown away. Other witnesses a few tens of kilometers from the explosion reported that they were physically blown into the air and knocked unconscious; they awoke to find a transformed landscape of smoke and burning trees that had been blasted to the ground.

At the time of the explosion, Russia was in the midst of political upheaval. As a result, there was no quick response to or investigation of the Tunguska event. Finally, in 1924, geologists who were working in the region interviewed surviving witnesses and determined that the blast from the explosion was probably heard over an area of at least 1 million km^2 (386,000 mi^2) and that the fireball had been witnessed by hundreds of people. Russian scientists went into the area in 1927, expecting to find an impact crater produced by the asteroid that had apparently struck the area. Surprisingly, they found no crater, leading them to conclude that the devastation had been caused by an aerial explosion, probably at an elevation of about 7 km (4.3 mi). Later calculations estimated the size of the asteroid responsible for the explosion to be about

12.1 Earth's Place in Space

We introduced a quick history of the origin of the universe and Earth in Chapter 1, and you may wish to review that discussion. The story is a magnificent one, with much of the mystery now removed but the wonder remaining. It is a story of how Earth, our home, evolved from a barren, nonliving planet into one filled with and modified by life (**Figure 12.2**). It is a story of change, with periodic drama caused by continued impact of material from outer space.[4,5]

Asteroids, Meteoroids, and Comets

There are literally trillions of particles in our solar system, ranging in size from dust that is a fraction of a millimeter in diameter to larger bodies such as **asteroids** that range in diameter from about 10 m (32 ft) to 1,000 km (621 mi). For the most part, asteroids are found in the *asteroid belt*, which is a region between Mars and Jupiter (**Figure 12.3**, page 406). The asteroids, which are composed of either rock material, metallic material, or rocky-metal mixtures, would pose no threat to Earth if they remained in the asteroid belt. Unfortunately, they move around and collide with one another, and a number of them are now in orbits that intersect Earth's orbit. When asteroids break into smaller particles they are known as **meteoroids** (**Table 12.1**, page 406), which range in size from dust particles to objects a few meters in diameter. When a meteoroid enters Earth's atmosphere, it is known as a **meteor**. As they streak through the atmosphere, meteors—sometimes called shooting stars—produce light that results from frictional heating. Sometimes meteors occur in large numbers, producing *meteor showers*.

The orbits of **comets**, which range in size from a few meters to a few hundred kilometers in diameter, also sometimes intersect Earth's orbit. Comets are thought to be composed of a rocky core surrounded by ice and covered in carbon-rich dust.

FIGURE 12.1 Tunguska forest, Siberia 1908 An aerial blast downed trees over an area of about 2,000 km^2 (770 mi^2). *(Sovfoto/Eastfoto)*

25 to 50 m (82 to 164 ft) in diameter. It was most likely composed of relatively friable (i.e., easy to crumble) stony material.[1,2]

The people of Earth were lucky that the Tunguska event occurred in a sparsely populated, forested region. If the blast had occurred over a city such as London, Paris, or Tokyo, the lives of millions of people would have been lost. Tunguska-type events are thought to occur on the order of every 1,000 years.[3] A widely reported near miss of a potentially dangerous asteroid occurred in March 2004. The asteroid was 30 m (100 ft.) in diameter and passed between Earth and the moon at a distance of about 43,000 km (25,000 mi).*

*For a great interactive Web site for near-Earth objects, see http://neo.jpl.nasa.gov.

FIGURE 12.2 Earth rise from the moon Earth is the blue planet compared to a lifeless moon. *(World Perspectives/Getty Images)*

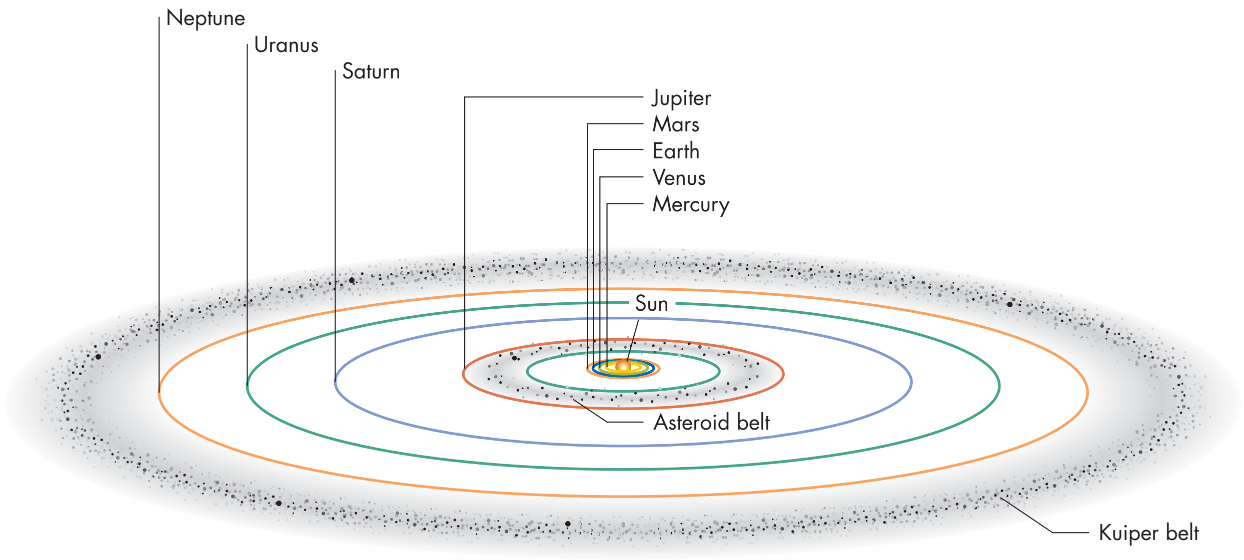


FIGURE 12.3 Solar system Idealized diagram (not to scale) of our planetary system showing the asteroid belt and Kuiper belt. The Oort Cloud is too far out to show. Orbits of planets are not to scale. *(Modified after Marshak, S. 2001.* Earth. *New York: W. W. Norton & Co.)*

TABLE 12.1 Meteorites and Related Objects

Type	Diameter	Composition	Comments
Asteroid	10 m–1,000 km	Metallic or rocky	Strong and hard if metallic or solid rock. Some hard types may impact Earth. If they are friable, or weak, they likely will break up in the atmosphere of Earth at elevations of several kilometers to hundreds of kilometers. Most originate in the asteroid belt between Mars and Jupiter.
Comet	Few meters to few hundred kilometers	Frozen water and/or carbon dioxide plus small rock fragments and dust; "dirty snowball"; core is ice surrounded by rock particles	Weak, porous, will often explode in atmosphere of earth at elevations of several kilometers to several hundreds of kilometers. Most originate in the outer solar system such as the Oort Cloud 50,000 AU[1] from the Sun or from the Kuiper belt of comets. The comet tail is produced as ices sublimate (vaporize) and gases and dust particles are shed from the object.
Meteoroid	0.1 mm to 10 m (sand to boulder size)	Rocky, metallic, or carbonaceous (contains carbon)	Most originate from collisions of asteroids or comets. May be strong or very weak.
Meteor	Centimeter to dust size	Rocky, metallic, carbonaceous, or icy	Are destroyed in Earth's atmosphere. "Shooting star" light produced by frictional heating in the atmosphere.
Meteorite	Asteroid size (10 m-1,000 km) to larger than dust (0.005 mm)	Rocky or metallic	Actually impact Earth's surface. Most abundant type of stony meteorite is called *chondrite*.[2]

[1] AU is the distance from Earth to the Sun, about 150 million km (93 million mi).

[2] There are many types of chondrites. They contain chondrules, which are small (less than 1 mm) spheroidal inclusions that are glassy or crystalline. Planets are constructed from chondrite meteorites (asteroids).

Data from Rubin, A. F. 2002. *Disturbing the Solar System.* Princeton, NJ: Princeton University Press.

FIGURE 12.4 Comet Hale-Bopp 1997. *(Aaron Horowitz/Corbis)*

They are believed to have originated far out in the solar system, beyond Neptune in the Kuiper belt and Oort Cloud (Figure 12.3), which extends as far as 50,000 times the distance from the Earth to the Sun.[2] **Figure 12.4** shows the comet Hale-Bopp, visible from Earth in 1997. The characteristic tail of the comet is composed of dust and gas that escape as the comet is warmed by the Sun and moves through space.

Early in the history of the evolution of Earth, bombardment by asteroids and comets contributed the building blocks of our planet, which was built from the collision of innumerable bodies. Asteroids and comets contain water, and impacts through geologic time delivered the water that later formed our oceans by volcanic degassing.

12.2 Aerial Bursts and Impacts

When entering Earth's atmosphere, asteroids, comets, and meteoroids travel at velocities that range from about 12 to 72 km per second (26,000 to 156,000 mi per hour).[1] A speeding bullet from a high-powered rifle would initially be as much as 1.5 km per second. Asteroids and meteoroids are variable in composition (Table 12.1). Some contain carbonaceous material, and others are composed of native metals such as iron and nickel. Others are stony, consisting of silicate minerals such as olivine and pyroxene—common minerals in igneous rocks. Stony meteoroids and asteroids are said to be *differentiated*, meaning that they have undergone igneous and sometimes metamorphic processes as part of their geologic histories. As previously mentioned, meteoroids and asteroids come from the asteroid belt, which is between the orbits of Mars and Jupiter, whereas comets come from the Kuiper belt or Oort Cloud. Regardless of where they come from, when they intersect Earth's orbit and enter our atmosphere, meteoroids, asteroids, and comets undergo remarkable changes as they heat up due to friction during descent, producing bright light. If the object actually strikes Earth, then we speak of it as a **meteorite**. Many meteorites have been collected from around the world, particularly from Antarctica. **Figure 12.5** shows a hypothetical diagram of a meteoroid entering the atmosphere about 85 km (53 mi) above Earth's surface. The meteoroid becomes a meteor and emits light. It will either result in an airburst in the atmosphere at an altitude between 12 and 50 km (7.5 and 31 mi) or collide with Earth to become a meteorite. The Tunguska event that opened this chapter was a giant airburst, but the surface of Earth has a significant number of meteorite craters, and more than 100 have been identified.[1]

Impact Craters

The most direct and obvious evidence for impacts on the surface of Earth comes from studying the craters they produce. The 50,000-year-old Barringer Crater in Arizona is perhaps the most famous meteorite crater in the United States. Known as "Meteor Crater," it is an extremely well-preserved, bowl-shaped depression with a pronounced, upraised rim (**Figure 12.6a**, page 409). The rim of the crater is overlain by an ejecta blanket (i.e., layer of debris blown out of the crater upon impact) that today can be identified as hummocky terrain surrounding the crater. Figure 12.6b shows that the present crater is

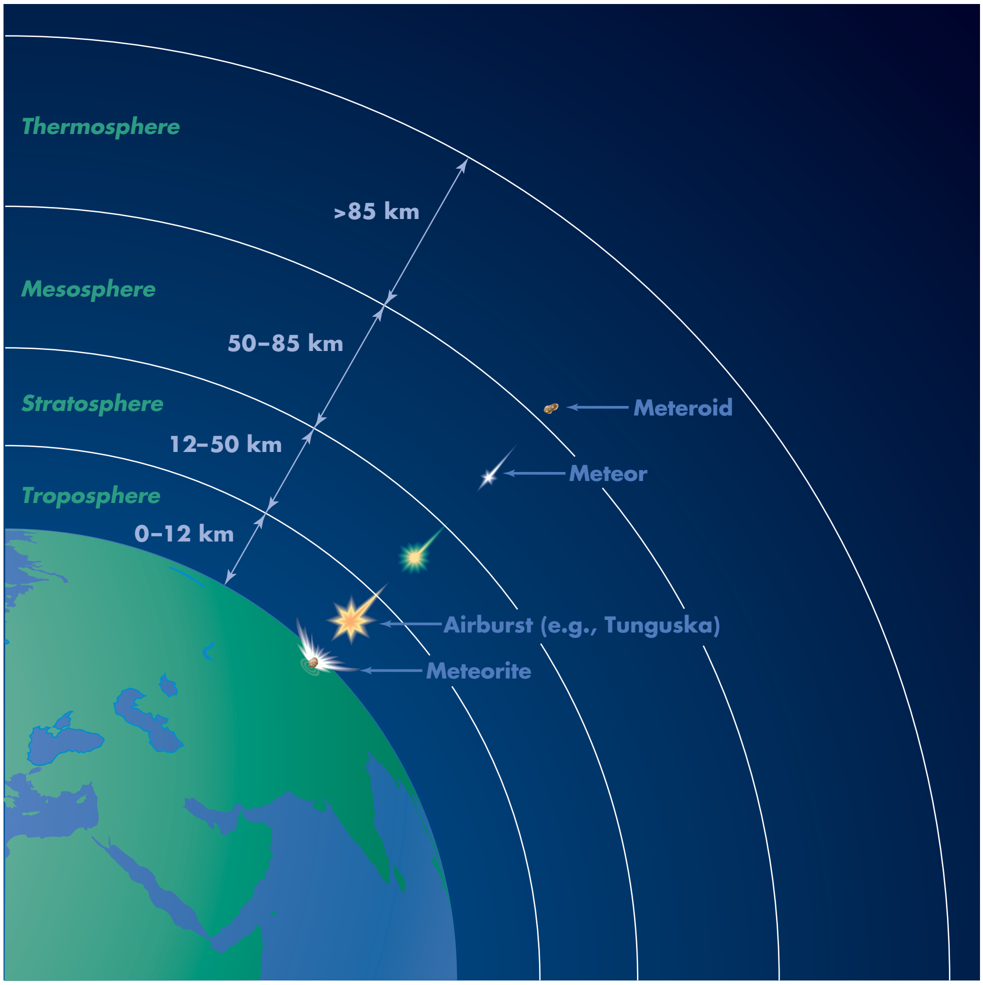


FIGURE 12.5 Meteoride Idealized diagram showing a meteoroid entering Earth's atmosphere. It may become a meteor, cause an airburst, or impact the surface of Earth. *(Modified after R. Baldini, www-th.bo.infn.it/tunguska/impact/fig1_2.jpg)*

not nearly as deep as the initial impact crater. This is because material has fallen back into the crater and because the crater has partially collapsed. The rocks that the asteroid impacted were shattered and deformed, forming what is known as brecciated rock, composed of angular broken pieces of rocks produced during the impact. Barringer Crater is approximately 1.2 km (0.75 mi) in diameter, with a depth of about 180 m (590 ft). The rim of the crater rises about 260 m (850 ft) above the surrounding topography. When Americans first discovered Barringer Crater in the late nineteenth century, there was a lot of debate concerning its origin. Ironically, G. K. Gilbert, the famous geologist who postulated that the majority of the moon's craters were formed by impacts, did not believe that Barringer Crater was formed by impact. Only through careful study and evaluation was it finally concluded that Barringer Crater in fact resulted from the impact of a small asteroid, probably about 25 to 100 m (80 to 330 ft) in diameter.[6]

The process of impact differentiates impact craters from craters that result from other processes, such as volcanic activity. This is because the processes related to impacts involve extremely high velocity, energy, pressure, and temperature, which normally are not experienced or produced by other geologic processes. Most of the energy of the impact is in the form of kinetic energy, or energy of movement. This energy is transferred to Earth's sur-

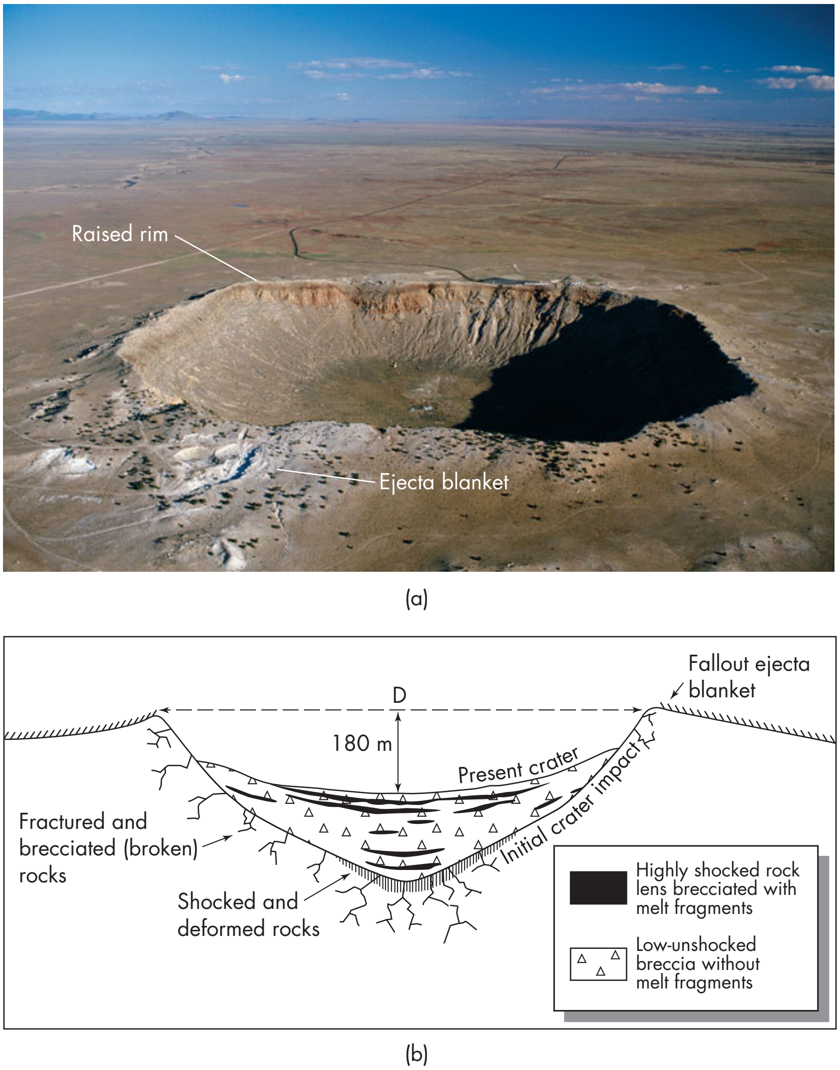
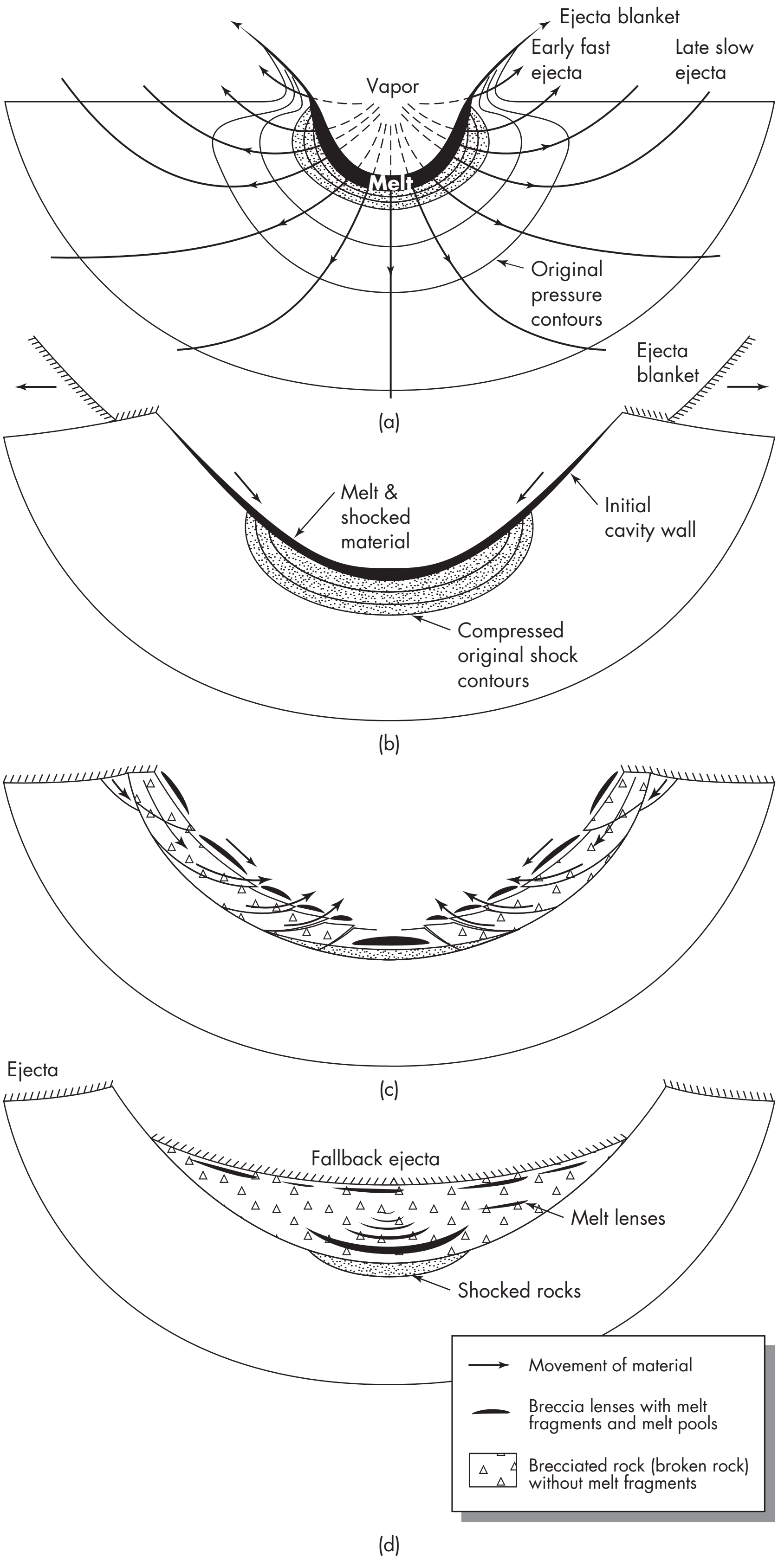


FIGURE 12.6 Crater in Arizona (a) Barringer Crater, Arizona (about 50,000 years old). The crater is about 1.2 km (0.75 mi) across and 180 m (590 ft) deep. *(Charles O'Rear/Corbis)* (b) Diagram (cross section) showing some of the features of the crater. *(Modified after Grieve, R., and Cintala, M. 1999.* Planetary impacts. *In Weissman, P. R., McFadden, L., and Johnson, T. V. (eds.)* Encyclopedia of the Solar System. *San Diego, CA: Academic Press)*

face through a shock wave that propagates into Earth. The shock wave compresses, heats, melts, and excavates Earth materials. It is this transfer of kinetic energy that produces the crater.[6] The shock can metamorphose some of the rocks in the impact area while others are melted or vaporized and mixed with the materials of the impacting object itself. Most of the metamorphism consists of high-pressure modifications of minerals such as quartz. Such modifications are characteristic of meteorite impact and are extremely helpful in confirming the origin of a meteorite crater. A typical small crater, a few kilometers in diameter, is idealized in **Figure 12.7a**. The same process of vaporization, melting, ejection of material, formation of ejecta rims, and infilling of the crater also occurs for large, more complex craters, but the shape of a larger crater may be quite different (**Figure 12.7b**, page 411). Complex craters over a period of seconds to several minutes following impact may grow to sizes of tens of kilometers to over 100 km (62 mi) in diameter. A pattern of more complete rim collapse and central crater uplift occurs following the impact. In general, impact craters on Earth that are larger than about 6 km (3.7 mi) are complex, whereas smaller craters tend to be more simple.

Geologically, ancient impact craters are difficult to identify because they have often been either eroded or filled with sedimentary rocks that are younger than the impact. For example, subsurface imaging and drilling below the present Chesapeake Bay have identified a crater about 85 km (53 mi) in

FIGURE 12.7a Simple crater Idealized diagram (cross-sections a-d) of the evolution of a simple crater over a time interval of seconds to a minute or so. *(Modified after Grieve, R., and Cintala, M. 1999.* Planetary impacts. *In* Weissman, P. R., McFaddden, L., and Johnson, T. V. *(eds.)* Encyclopedia of the Solar System. *San Diego, CA: Academic Press)*



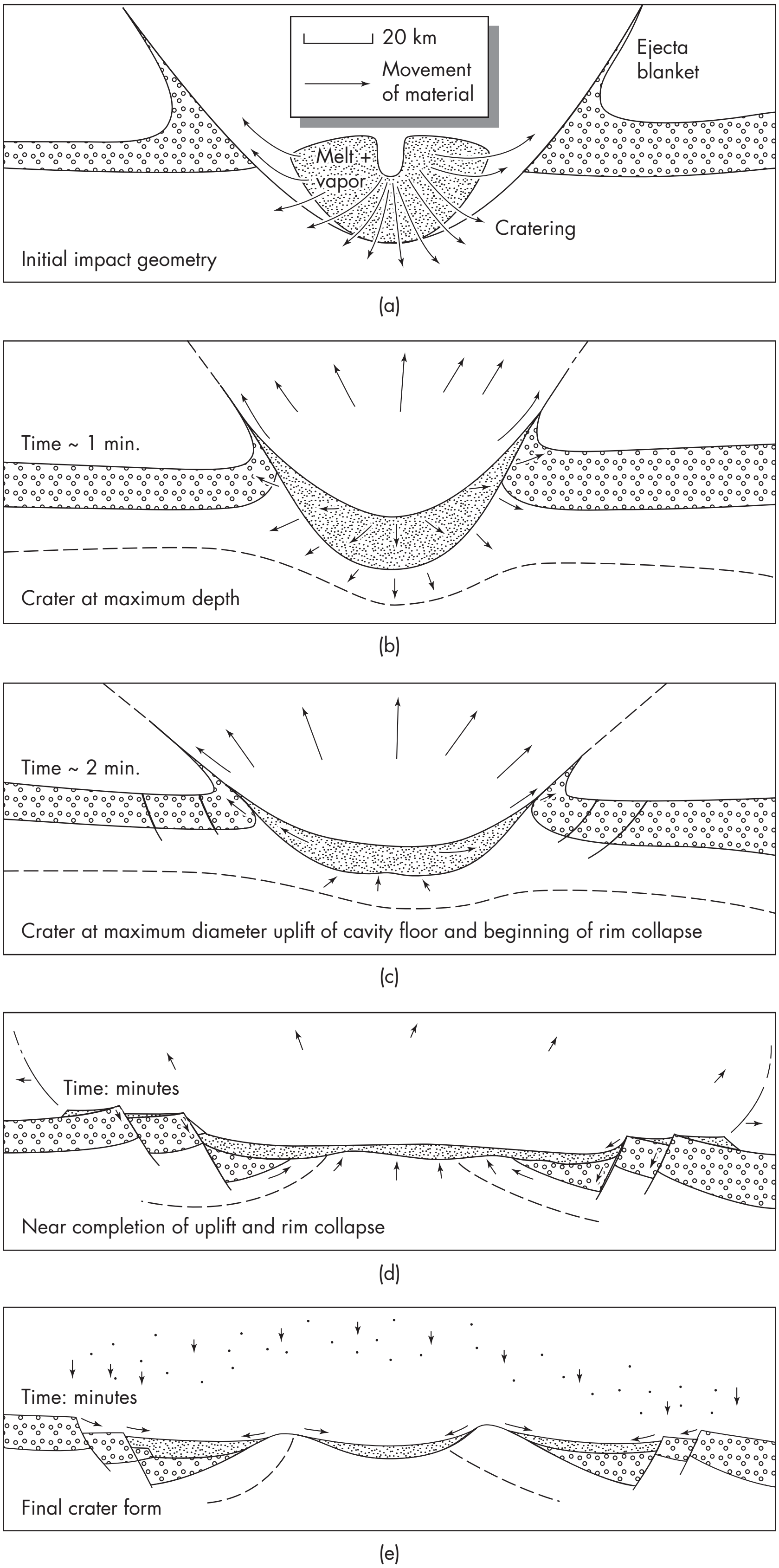
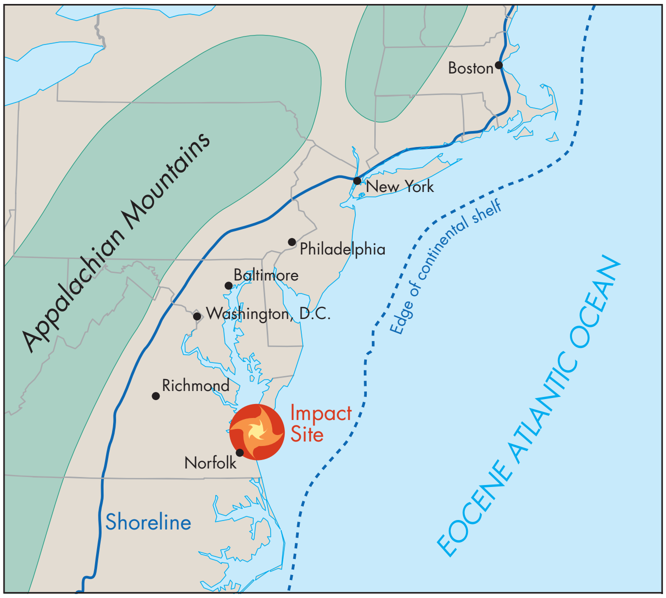
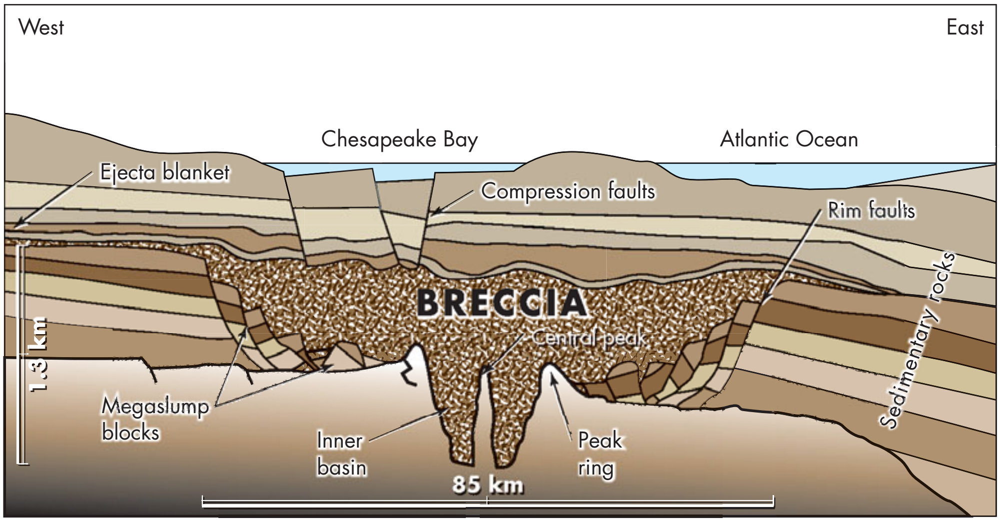


FIGURE 12.7b Complex crater
Idealized diagram (cross sections a-e) of the evolution of a complex crater over several minutes. *(Modified after Grieve, R., and Cintala, M. 1999.* Planetary impacts. *In Weissman, P. R., McFaddden, L., and Johnson, T. V. (eds.)* Encyclopedia of the Solar System. *San Diego, CA: Academic Press)*

FIGURE 12.8 Chesapeake Bay Map (a) and idealized diagram (b) of the Chesapeake Bay impact structure that formed about 35 million years ago. *(Williams, S., Barnes, P., and Prager, E. J. 2000. U.S. Geological Survey Circular 1199)*



(a)

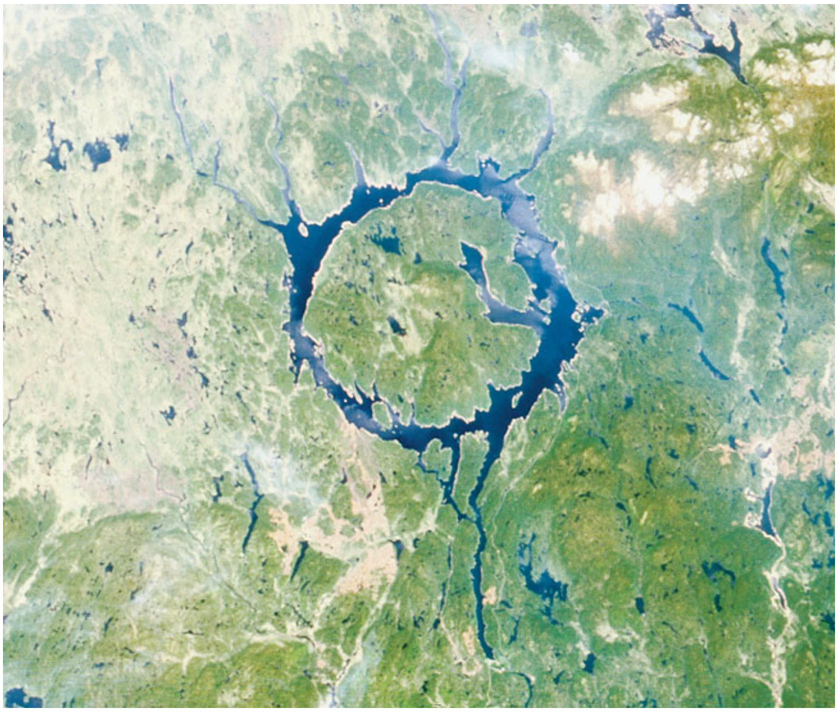


(b)

diameter, now buried by about 1 km (0.62 mi) of sediment (**Figure 12.8**). The crater was produced by impact of a comet or an asteroid about 3 to 5 km (1.9 to 3 mi) in diameter about 35 million years ago.[7] Compaction and faulting above the buried crater may be in part responsible for the location of the bay.

A good example of an eroded impact crater is found near Quebec, Canada. A ring-shaped lake about 70 km (45 mi) across is eroded along impact-brecciated (broken) rocks, marking most of the crater, which is about 100 km (62 mi) in diameter (**Figure 12.9**).[8]

Most detailed remote-sensing studies of craters come from evaluation of these features on the moon and Mars. Impact craters are much more common on the moon than on Earth because as smaller objects enter Earth's atmosphere, they tend to burn up and disintegrate before actually striking the surface. Studying impact features on the moon and Mars has greatly increased our understanding of the process of impact and the associated surface features.



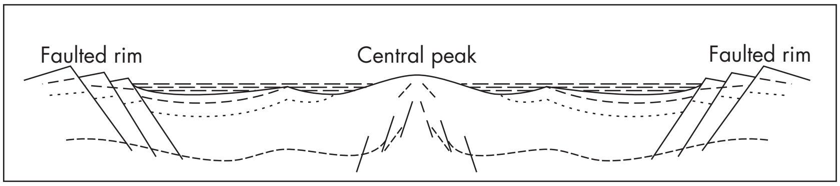


FIGURE 12.9 Canada impact structure Satellite image and diagram of the Manicougan impact structure in Quebec, Canada. The ring-shaped lake is about 70 km (45 mi) across. *(NASA)*

Early in 1994, a comet known as Shoemaker-Levy 9 (discovered in 1993) provided visual evidence of the most tremendous impacts ever witnessed. The comet was unusual in that it was composed of several discrete comet fragments with several bright tails. It was reported as a misshapen comet. It was determined that the comet was a member of the Jupiter family of comets (comets that circle between Jupiter and the Sun), about 50 of which are known. The orbit of the comet was tied to that of Jupiter, and after years of orbiting the planet, it separated into 21 fragments known as a "string of pearls." As the fragments of the comet entered Jupiter's atmosphere at speeds of about 60 km/sec (37 mi/sec), they exploded, releasing energy on the order of 10,000 megatons for the smaller fragments and as much as 100,000 megatons for the larger fragments (**Figure 12.10**). The total amount of energy released was estimated to be more than would be released by Earth's entire store of nuclear weapons if detonated at one time. Hot, compressed gaseous emissions expanded violently upward from the lower part of Jupiter's atmosphere at speeds as high as 10 km/sec (6.2 mi/sec). These plumes of gas from the larger impacts reached elevations of more than 3,000 km (1,864 mi), as tremendously large rings that exceed the diameter of Earth developed around the sites of the impact. It was truly a remarkable show for astronomers and a sobering event for those who consider that impacts such as this might one day occur on Earth.[2]

Now that we have viewed the impact of the fragmented comet on Jupiter and studied Barringer Crater in Arizona as well as several others on Earth, the idea of the possibility of catastrophic impacts on Earth is finally being accepted. When the Tunguska event that opened this chapter occurred, several bizarre ideas were suggested to explain it, including nuclear explosions and even the explosion of an alien spaceship! The idea that impacts by asteroids

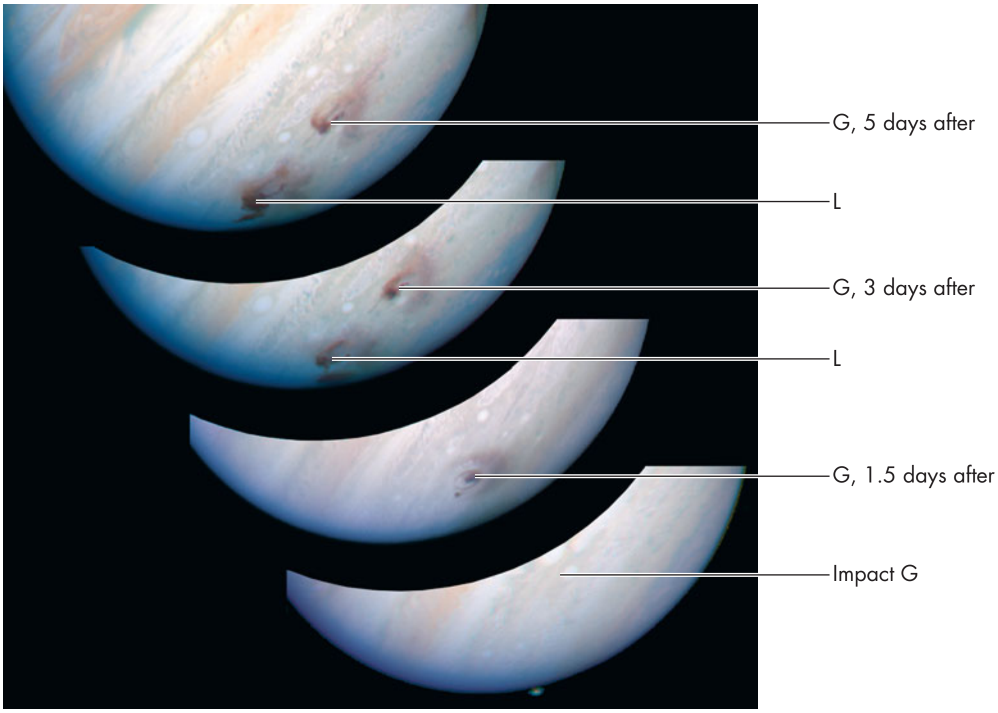


FIGURE 12.10 Impact on Jupiter Shoemaker-Levy 9G impact on Jupiter, "string of pearls" comet. *(R. Evans, J. Trauger, H. Hammel, and the HST Comet Science Team/NASA)*

and comets might cause catastrophes on Earth, and even mass extinction of life, was greatly resisted by scientists until very recently.

12.3 Mass Extinctions

A mass extinction is characterized by the sudden loss of large numbers of plants and animals relative to the number of new species being added.[9] Because the geologic time scale was originally based on fossils and the appearance and disappearance of different species, mass extinctions correlate to boundaries in the geologic time scale, as shown in Table 2.1 and Figure 1A. Many hypotheses have been suggested for mass extinction events, including (1) relatively rapid climate change; (2) plate tectonics, a relatively slow process that moves the position of continents and thus environments to different locations; (3) extremely large volcanic events that erupted huge volumes of volcanic ash into the atmosphere and changed the climate; and (4) impact of a large extraterrestrial object.

During the past 550 million years of Earth history, there have been six major mass extinction events. The four earliest extinction events are being studied intensively to test the hypothesis that impacts of large asteroids or comets were involved. As dating of extinction events improves, we may to be able to determine how fast the extinction occurred. A fast mass extinction favors impact by an extraterrestrial object as a cause of extinction.

The earliest mass extinction occurred approximately 443 million years ago, near the end of the Ordovician period. Although not much is known about the cause of this extinction, it may have been related to global cooling. Approximately 100 families and their associated species became extinct during this period. The next mass extinction occurred about 90 million years later, near the end of the Devonian. That extinction was responsible for the death of about 70 percent of all (marine) invertebrate species and was also probably related to climate change and global cooling. The third mass extinction occurred near the end of the Permian—about 245 million years ago—when 95 percent of all marine species died. Although there is now an argument for impact at the Permian–Triassic boundary, it is also believed that this mass extinction possibly spanned a period of about 7 million years. It is thought that global cooling, followed by rapid global warming with large variations in climate, may have been responsible. There was also significant volcanic

activity during this time, and the tremendous amount of volcanic ash and gases in the atmosphere probably contributed to the cooling. At the end of the Cretaceous period (i.e., the K-T boundary), another tremendous mass extinction event occurred. This event was sudden, and there is abundant evidence to suggest that it was caused by the impact of a giant asteroid. Another mass extinction occurred near the end of the Eocene, about 35 million years ago. There is limited evidence that impact from an asteroid or a comet may have occurred at that time, but many scientists link the extinction to cooling and glaciation, which occurred approximately 40 to 30 million years ago. Finally, near the end of the Pleistocene and into the present, there was an ongoing mass extinction of mammals, reptiles, amphibians, birds, fish, and plants. It is possible that overhunting by Stone Age man may have been a partial cause of this event. However, the loss of so many large mammals in North America, including some that were not hunted, may point to other causes more catastrophic in nature. (See A Closer Look: Possible Extraterrestrial Impact 12,900 Years Ago.) More recently, in the past 200 years, loss of habitat as a result of land use changes, widespread deforestation, and application of chemicals has contributed to ongoing extinction.[9]

While some of these extinction events are believed to have been related to climate changes, the case for impact-related mass extinction 65 million years ago at the end of K-T boundary is well documented. The K-T extinction brought an end to the dinosaurs, which had been at the top of the food chain for 100 million years or more. Their demise allowed small mammals to expand and evolve into many species, including humans, that are present on nearly all land areas of Earth today. A similar evolution also occurred in the oceans of the world. We will now address the K-T extinction and the impact hypothesis in more detail.

Late Cretaceous: K-T Boundary Mass Extinction

One of the great geologic detective stories of the past 50 years is the investigation of the K-T mass extinction. We now believe that 65 million years ago, a comet or an asteroid with a diameter of about 10 km (6.2 mi) impacted Earth in the vicinity of what is now the Yucatan Peninsula. That event changed Earth history forever. Although after the event much of the physical landscape of Earth remained unchanged, the planet's inhabitants were changed forever. The dinosaurs disappeared, as did many species of plants and animals in both the oceans and on land. Approximately 70 percent of all genera on the planet and their associated species died off. Somehow, animals such as turtles, alligators, and crocodiles survived, as well as some birds, plants, and smaller mammals. It is not known why some life forms survived the mass extinction and others did not. What we do know is that the demise of the dinosaurs on land and reptiles and dinosaurs in the oceans set the stage for mammals that eventually produced primates and humans. What would the world look like today if the K-T extinction had never happened? There's a good chance that humans never would have evolved!

Now let's back up and look at the history and development of the hypothesis that the K-T mass extinction event was indeed caused by the impact of a large comet or asteroid. The story is full of intrigue, suspense, rivalries, and cooperation—typical of many of the great scientific discoveries.[10] A number of scientists with backgrounds in geology, physics, chemistry, biology, geophysics, and astronomy worked together to develop and test the hypothesis that the K-T mass extinction was triggered by an impact. Walter Alvarez asked the question that started it all: "What is the nature of the boundary between rocks of the Cretaceous and Tertiary periods (65 million years ago)?"*

Alvarez was interested in Earth history and was particularly interested in reading that history as recorded by rocks. Early in his studies of the K-T boundary, Alvarez teamed up with his physicist father, Luis, and nuclear chemists Frank Asaro and Helen Michel. They decided to measure the concentration of a platinum metal called iridium in the thin clay layer that represented the K-T boundary in Italy. Walter Alvarez and colleagues initially went to the site in Italy to study the magnetic history of Earth. What they found at the K-T boundary was a very thin layer of clay. It looked as if the extinction

*Walter Alvarez wrote a book titled *T. Rex and the Crater of Doom*, which was published in 1997 (Alvarez, 1997). While our discussion will present some of the highlights of this story, interested readers are invited to see Alvarez's book for the complete story.

A Closer Look

Possible Extraterrestrial Impact 12,900 Years Ago

North America is ecologically different today than it was 13,000 years ago, when it was populated by Pleistocene megafauna that included mammoths (a type of elephant; **Figure 12.A**), dire wolves, American lions, short-faced bears (which were larger than modern grizzly bears), giant ground sloths, camels, and horses. Also present were Paleo Americans, especially the Clovis culture. Suddenly and, perhaps, catastrophically, most of the megafauna disappeared, and the Clovis culture was no longer recognizable. The climate abruptly cooled, forming the cold period known as the Younger Dryas (named after tundra fossil pollen of the dryas plant).[15] The possible causes of the extinction of the megafauna and the termination of the Clovis culture has been a long-standing and controversial subject. The two major competing hypotheses to explain the extinction of the magafauna are overkill by humans and abrupt cooling (i.e., rapid climate change). Both of these hypotheses have shortcomings. Human overkill seems unlikely in light of the very large numbers of animals that went extinct, including many that the Paleo Americans evidently did not regularly hunt. The magnitude of the abrupt cooling at the onset of the Younger Dryas was little different than what had often occurred over the previous 80,000 years, and none of the earlier events were associated with major extinctions. The conclusion is that the extinction of Pleistocene megafauna is unique during the latest Pleistocene period and was too abrupt and widely distributed to have resulted from human overkill or climatic cooling.[15]

FIGURE 12.A Most megafauna in North America, including the wooly mammoth illustrated here, suddenly went extinct 12,900 years ago. *(Jonathan Blair/Corbis)*

At many Clovis sites, archeologists have identified what is known as a black mat that is a thin layer of carbonaceous, dark, organic-rich clays (**Figure 12.B**). The base of the black mat coincides with the beginning of Younger Dryas cooling, after which there is no evidence for "in place" remains of the megafauna or artifacts from the Clovis culture. Murray Springs, Arizona, is a well-known and well-studied Clovis site, where the youngest mammoth bones and Clovis tools are directly in contact with the base of the black layer. At that site, it is apparent that termination of Pleistocene megafauna and Clovis culture was very sudden, coinciding with the deposition of the black mat.[15,16]

New evidence that has emerged in the past several years suggests that there may have been an extraterrestrial (cosmic) impact 12,900 years ago that contributed to the Pleistocene megafauna extinctions, as well as to the disappearance of the Clovis culture.[11] Evaluation of 10 Clovis sites, selected because they were well documented and dated, support the hypotheses that there may have been a major extraterrestrial collision over North America 12,900 years ago, at the beginning of the Younger Dryas event. Hypothetically, the event consisted of one or more (perhaps many) low-density extraterrestrial objects (probably

FIGURE 12.B Murray Springs, Arizona, in 1968 Clovis site, with black mat and bones of Pleistocene megafauna. *(Allen West)*

comets) that exploded in the atmosphere over much of North America. At that time, much of Canada was covered by the Laurentide Ice Sheet, which was partially destabilized by the proposed event. It is speculated that many objects exploded over the continent, including the ice sheet, setting off heat flashes and shock waves and generating intense winds (hundreds of kilometers per hour) over North America. The event also would have spawned fireballs that destroyed forests, grasslands, and animals, while producing an abundance of charcoal, ash, soot, and toxic fumes.[16] Evidence of this is found as far west as Santa Rosa Island in the Santa Barbara Channel.[17]

Physical evidence for the Younger Dryas event includes the discovery of a variety of possible extraterrestrial markers, including magnetic grains with iridium, magnetic micro spherules, carbon spherules, charcoal and soot, and evidence for intense wildfires. An abundance of diamonds, including nano diamonds (including forms normally interpreted to be formed only by cosmic impact), micro diamonds, and shock diamonds (also thought to form from cosmic impact), have been discovered within the black mat, but much less frequently above and below the mat.[13,14] As the hypothesis of the Younger Dryas event continues to be tested, more data will be forthcoming, and we will learn more about the catastrophic event that brought about the demise of the Pleistocene megafauna, the end of the Clovis culture, and the climatic change from warm to colder glacial conditions that lasted for about 1,000 years.[16,18] Although no craters of Younger Dryas age have yet been found in North America near the suspected impact region, as the hypothesis is thoroughly tested over the next decade, it is likely that more direct physical evidence of the cosmic impact will be discovered.

of many species was very abrupt at the clay layer. Fossils found in rocks below the clay were not in rocks above the clay. They then asked the question: "How much time was involved in the deposition of the clay layer? Was it a few years, a few thousand years, or millions of years?"

They decided to try to determine the timing of the clay deposition by measuring the amount of iridium in the clay. Iridium is found in very small concentrations in meteorites; assuming that the rate of accumulation of small meteoritic dust on Earth is constant, it would be possible to determine the age of the clay from its oldest to its youngest part by looking at the amount of iridium. What they found was entirely unexpected. The team anticipated measuring approximately 0.1 parts per billion of iridium in the clay layer, which they thought would represent slow accumulation through time. If the clay layer was deposited rapidly, the amount of iridium would be even less. What they actually

found was about 3 parts per billion—30 times more than expected. Even 3 parts per billion is a very small amount, but it was much more than could be explained by their previous hypothesis of slow deposition over time. They reevaluated the data. This time, they included samples that were removed for treatment before measurement and got a final value of about 9 parts per billion, which is nearly 100 times greater than expected. This discovery led them to a new hypothesis: that the iridium might be the result of an asteroid impact.

The team's iridium discovery, along with the hypothesis that there might be an extraterrestrial cause for the extinction at the K-T boundary, was published in 1980.[11] In that paper, the team also reported elevated concentrations of iridium in deep-sea sediments in Denmark and New Zealand, all of which are at the K-T boundary. With the discovery that the iridium anomaly occurred at several places around the world, the team became more confident of its impact hypothesis; however, it had no crater. This ushered in a period of research from other scientists, directed at finding potential craters that formed 65 million years ago. There was some concern that a crater might have been completely filled with sediment and no longer recognizable, or that a crater was at the bottom of the ocean and may have been destroyed by plate tectonics. Fortunately, the site of the crater was identified in 1991.[12]

Geologists in Mexico studying the structural geology of the Yucatan Peninsula discovered what they determined to be a buried impact crater with a diameter of approximately 180 km (110 mi). The crater is nearly circular, and there is a clear boundary between unfractured rocks within the crater and fractured rocks outside the crater. About half of the crater lies in the Gulf of Mexico and half on the northern end of the Yucatan Peninsula (**Figure 12.11**). On land, the researchers found a semicircular pattern of sinkholes, known to the Maya people as *cenotes*, that correspond directly to the edge of the proposed impact crater. The *cenotes* range from about 50 to 500 m (164 to 1,640 ft) in diameter and were presumably formed by chemical weathering of the limestone by water flowing through the fractured rock on the outside of the crater boundary. It was

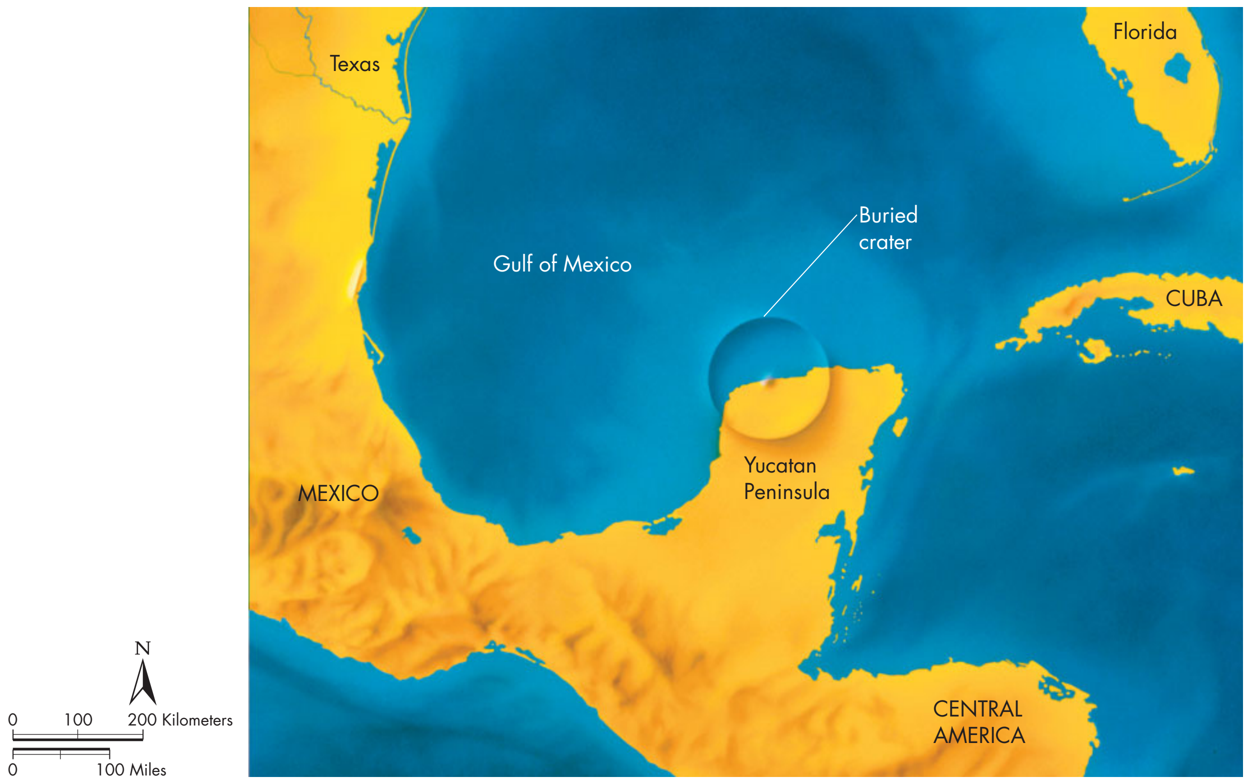


FIGURE 12.11 Crater in Mexico Map showing location of the buried impact crater from the asteroid that caused the K-T mass extinction. *(© D. Van Ravenaswaay/Science Photo Library/Photo Researchers, Inc.)*

reasoned that the fracturing that created the ring of *cenotes* must be related to the circular structure since there is no other known structure that could explain the curved pattern of the features. The crater, which is now filled with other rocks, is believed to have been as deep as 30 to 40 km (18 to 25 mi) at the time of impact. However, subsequent slumping and sliding of materials from the sides soon filled in much of the crater, and sedimentation over the past 65 million years completely buried the structure.

Drill cores were taken and samples of glassy melt rock were retrieved from below another massive layer that was interpreted to be impact breccia within the proposed crater. The force of the impact excavated the crater, fractured the rock on the outside, and produced the breccia, which is a rock composed of angular pieces of rocks that have been cemented together. The glassy melt rock suggests that sufficient heat was present to actually melt rocks as a result of the impact.[13] Another study of the crater found glass mixed with and overlain by the breccia, as well as evidence of shock metamorphism commonly associated with impact features.[14] The results of these studies of the Yucatan Peninsula crater (known as the Chicxulub Crater) are accepted, and it is hypothesized that the impact from the asteroid that struck the area 65 million years ago did in fact cause or significantly contribute to the K-T mass extinction.

After identifying the site of the crater and the evidence to support its existence, questions naturally arose regarding how such an event could cause a global mass extinction.[15] The asteroid that struck the Yucatan Peninsula 65 million years ago was huge; it is estimated to have had a diameter of about 10 km (6 mi). As a comparison, jet airplanes travel at cruising altitudes of about 30,000 ft, which is about 10 km above Earth's surface. The summit of Mt. Everest is not as high as 10 km, but it's close. Consider, too, that the asteroid struck the atmosphere of Earth at a speed of about 30 km/sec (19 mi/sec), which is about 150 times faster than a jet airliner travels. The amount of energy released is estimated to have been about 100 million megatons—roughly 10,000 times as great as the entire nuclear arsenal of the world. The likely sequence of events of the impact and aftermath is shown in **Figure 12.12**. The hole blasted in Earth's crust was nearly 200 km (125 mi) across and 40 km (25 mi) deep. At an altitude of 10 km (6 mi) in the upper atmosphere and moving at about 30 km/sec (19 mi/sec), it would have taken less than half a second for the collision on Earth to take place, producing the large crater almost instantaneously. Moving at such high speed, the asteroid would have penetrated the entire atmosphere in only a second or two. When contact occurred, shock waves quickly crushed the rocks beneath, filling in all the cracks, partially melting the rocks, producing the breccia, and blasting bits and pieces high into the atmosphere. All this probably took about 2 seconds, as the shock wave and heat vaporized rocks on the outer fringes of the impact. A tremendous amount of debris built up in a huge blanket around the crater. A gigantic cloud of vaporized rocks and gases would have produced an equally huge fireball that rose, producing a huge mushroom cloud. The explosion itself and the rising materials would probably have been sufficient to accelerate and eject material far beyond the surface of Earth. Particles of rock were blasted into ballistic trajectories before they fell back to the ground. The fireball would have produced sufficient heat to set fires around the globe. Vaporization of the limestone bedrock, which contained some sulfur, produced sulfuric acid in the atmosphere. Additional acids were added as a result of burning nitrogen in the atmosphere. Thus, following the impact, a long period of acid rainfall likely occurred. The dust in the atmosphere circled Earth, and for months there was essentially no sunlight reaching the lower atmosphere. The lack of sunlight stopped photosynthesis on land and in the ocean, and the acid rain was toxic to many living things, particularly terrestrial and shallow marine plants and animals. As a result, the food chain virtually stopped functioning because the base of the chain was greatly damaged. The impact occurred partly in the marine environment and significantly disturbed the seafloor, generating mega tsunami that could have reached heights of 1 km (3,000 ft). These waves would have raced across the Gulf of Mexico and inundated parts of North America.[10]

In summary, the impact of the asteroid caused a global catastrophic killing, which we refer to as a *mass extinction*. While there is some evidence that some species of dinosaurs were dying off before the impact, this event certainly seems to have been responsible for wiping out the remaining dinosaurs. Also, so many other species of animals and plants on land and in the oceans died that there is little doubt that a massive impact was the likely cause of

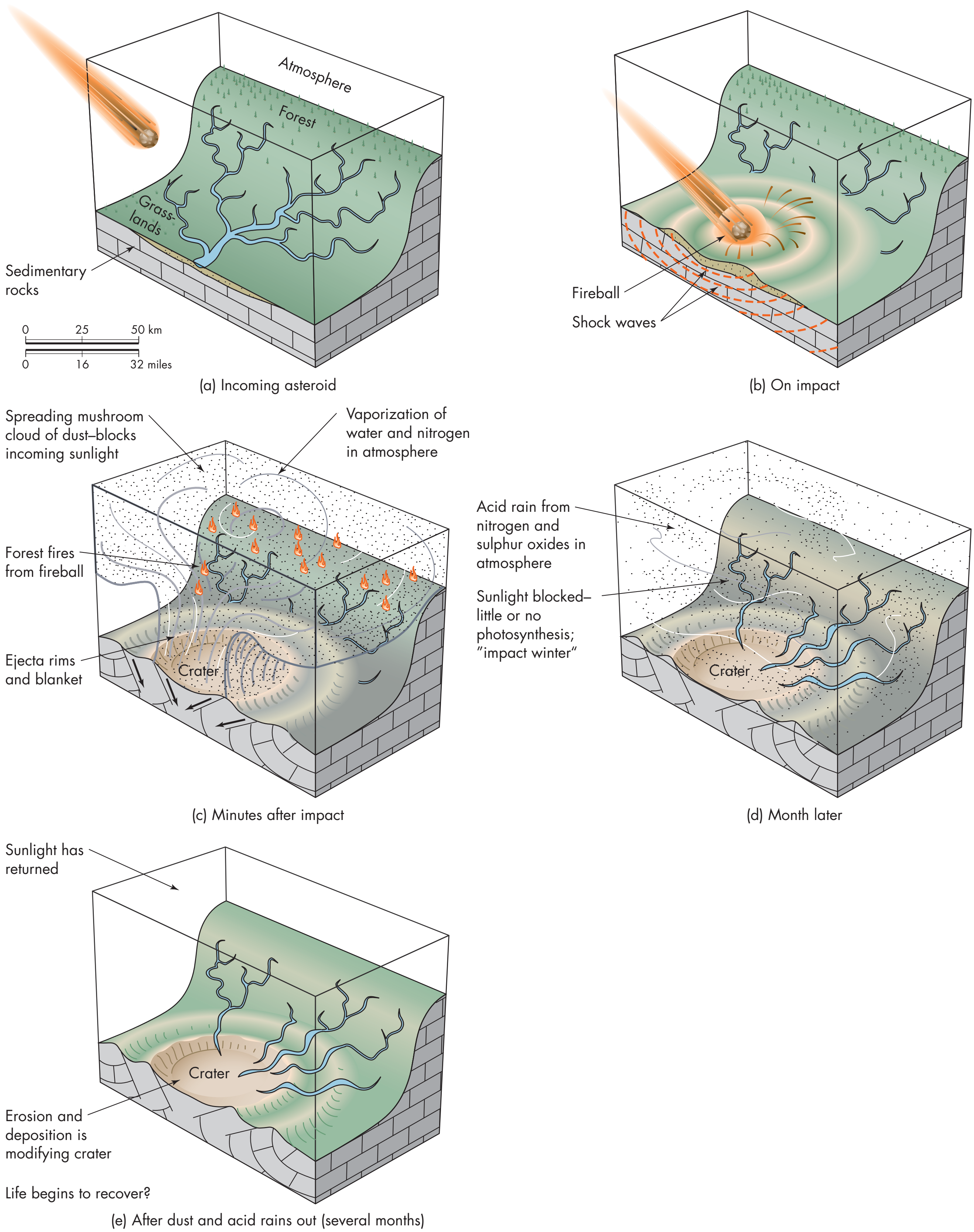


FIGURE 12.12 Sequence of events for a catastrophic impact (a) Incoming asteroid. (b) On impact. (c) Minutes after impact. (d) Months later. (e) After dust and acid rains out (several months).

the extinction. If such an event occurred again, the loss of life would be as significant. It might well mean the extinction of humans and many of the larger mammals and birds on the planet, leading the way to yet another pattern of evolution.

What we have learned from the K-T extinction is sobering. On the other hand, we know that impacts from objects as large as 10 km (6 mi) in diameter are very rare, occurring perhaps every 40 to 100 million years or so. However, large impacts are not the only hazard from comets, asteroids, and meteoroids. Smaller impacts are much more probable, and they can wreak havoc on a region, causing great loss of life and damage.

12.4 Minimizing the Impact Hazard

Risk Related to Impacts

The risk of an event is related to both the probability of an event occurring and the consequences if it occurs. The consequences of aerial bursts or direct impact from extraterrestrial objects several kilometers in diameter would be catastrophic. Although 7 out of 10 such events would likely occur in the oceans, results would be felt worldwide because of the enormous size of the object. Certainly there would be significant differences, depending on the site of impact, but the overall consequences would constitute a global catastrophe with high potential for mass extinction. Such events probably occur on Earth with return periods of tens to hundreds of millions of years (**Figure 12.13**). Whether smaller objects on the order of a few tens of meters produce an aerial blast or cause an impact crater, they would produce a regional catastrophe if the event occurred on land near a populated area. The size of the area devastated would be on the order of several thousand square kilometers and could cause millions of deaths if the event occurred over or in an urbanized region. We term these smaller but regionally significant events "Tunguska-type" events.

A recent study that evaluated aerial blasts from asteroids with diameters of about 50 to 100 m suggests that asteroids that are capable of causing catastrophic damages to a region occur on average about every 1,000 years (Figure 12.13). Using the Tunguska event as a characteristic event with a hit every thousand years somewhere on Earth, an urban area is

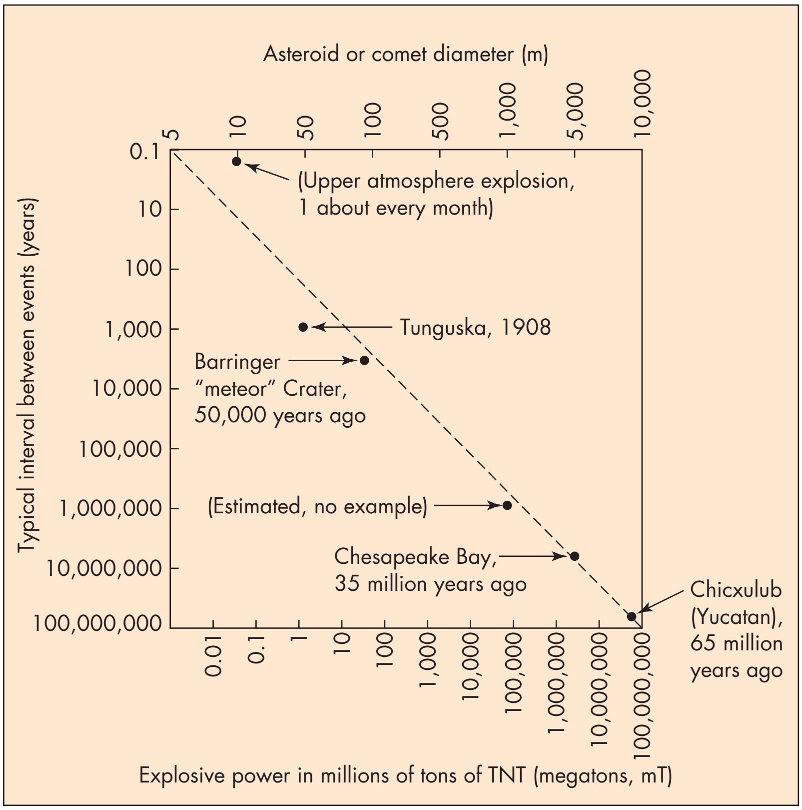


FIGURE 12.13 Energy from impact Estimate of relationship between energy of Earth impact and interval between events for various sizes of asteroids or comets. Also listed is the age of the events, which is not the same as the interval between events. *(Weissman, P. R., McFadden, L., and Johnson, T. V. (eds.) 1999.* Encyclopedia of the Solar System. *San Diego, CA: Academic Press; and Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E., and Worden, S. P. 2002. The flux of near-Earth objects colliding with the Earth.* Nature *420:294–296)*

likely to be destroyed every few tens of thousands of years. The dataset for this analysis comes from the distribution of 300 small asteroids that exploded in the atmosphere. Extrapolation of the data allows estimates to be made for larger, more damaging events.[3]

There is tremendous statistical variability in trying to predict the likelihood and type of future impacts, and when such estimates are made, the death tolls over a typical century may range from zero to as high as several hundred thousand. Computer-run simulations suggest that over a given century, there may be approximately 450 deaths per year due to impacts. A truly catastrophic event could kill millions of people. When this is averaged over thousands of years, it results in a relatively high average annual death toll. For example, if a large urban area with 10 million people is devastated, and such events are thought to occur every 30,000 years, then the average annual death toll for such an event is over 300 people per year. Put this way, the risk from impacts is relatively high. For example, the probability that you will be killed by an impact-driven catastrophe at the global level is approximately 0.01 percent to 0.1 percent. By comparison, the probability that you will be killed in a car accident is approximately 0.008 percent and by drowning is 0.001 percent. According to the probabilities, it appears that the risk of dying from a large impact or aerial blast from a comet or asteroid is considerably greater than other risks we normally face in life. However, we emphasize again that the risks related to impacts are spread out over thousands of years. Although the average death toll in any one year may appear high, it is just that—an *average*. Remember that such events (and related deaths) actually occur very infrequently. Certainly there is a risk, but the time period between events is so long that we shouldn't lose any sleep worrying about being involved in a global catastrophic event caused by an extraterrestrial object.

Minimizing the Impact Hazard

Now that we have some inkling of the probability of an impact of an asteroid or comet, what can we do to minimize the hazard? First and foremost is to identify near-Earth objects that might threaten Earth (see A Closer Look: Near-Earth Objects). Identification and categorization of comets and asteroids that cross Earth's orbit are already in progress and could be scaled up to include objects of different size classes, including those with diameters less than 50 m (164 ft), those 50 m to several hundred meters, and those with a diameter of several kilometers. A program known as Spacewatch, which has been operating since 1981, is attempting to take inventory of the region surrounding Earth with expansion to the entire solar system. Based on the inventory to date, scientists believe that there are around 135,000 objects with a diameter of 100 m (328 ft) or less that are Earth-crossing asteroids. Another program, known as the NEAT (Near-Earth Asteroid Tracking) system, began in 1996. The objective of this program, which is supported by the National Aeronautics and Space Administration (NASA), is to study the size distribution and dynamic processes associated with near-Earth objects and specifically to identify those objects with a diameter of about 1 km (3,280 ft). Both observation programs utilize cameras and telescopes. Images are analyzed to identify fast-moving objects.[8] The programs and systems to identify near-Earth objects are expected to intensify in the future, and more objects will be cataloged. This is a first step toward evaluating the potential hazard from near-Earth objects. However, evaluation will take a long time because many of the objects have orbits that may not bring them close to Earth for decades, and the average amount of time between potentially catastrophic impacts is at least thousands of years for the smallest objects. The good news is that most of the objects identified as being potentially hazardous to Earth will likely not collide with our planet until several thousand years after they have been discovered. Therefore, we will have an extended period of time to learn about a particular extraterrestrial object and to attempt to develop appropriate technology to minimize the hazard.[1]

By one estimate, there are about 20 million extraterrestrial bodies in near-Earth orbits that have the potential for a significant impact.[1] Only about 4 percent of these bodies are likely to penetrate Earth's atmosphere and excavate a crater. Over 50 percent are structurally weak and are prone to explode at altitudes of about 30 km (18.6 mi) above Earth's surface. While these are spectacular explosions, they are not a significant hazard at the surface of Earth. The remaining objects, which constitute about 40 percent of the total population of objects, are moderately strong chondritic asteroids

A Closer Look

Near-Earth Objects

Near-Earth objects (NEOs) are asteroids that either reside and orbit between Earth and the Sun or have orbits that intersect with Earth's orbit. There are literally millions of meteoroids, but it is the larger objects such as asteroids and comets that vary in size from a few tens of meters to a few kilometers in diameter that are of most significance to our discussion. If a near-Earth object with a diameter of a few tens of meters were to impact the atmosphere or surface of Earth, we would experience a Tunguska-type event. A near-Earth object of several kilometers in diameter would cause a global catastrophe. As mentioned earlier and shown in Figure 12.3, the origin of most asteroids is the asteroid belt, located between Mars and Jupiter. If the asteroids remained there, they would not become NEOs; however, their orbits may become disturbed because of collisions or near misses with other objects. This may cause the orbit of one or more bodies to become more elliptical and cross into the space between Earth and the Sun, or even cross the orbit of Earth. It is estimated that the number of Earth-crossing asteroids with diameters larger than 100 m (328 ft) is about 135,000. Larger Earth-crossing asteroids are more scarce, and it is estimated that there are about 1,500 with a diameter greater than 1 km (3,280 ft) and about 20 with a diameter greater than 5 km (3.1 mi).[8]

Comets are generally a few kilometers in diameter and can be described as giant snowballs in that they consist of mixtures of rock and ice (with more ice than rock by volume). Rock particles and dust cover the outside. Most comets are thought to originate far out in the solar system at a distance of about 50,000 AU (1 AU is the distance from the Earth to the Sun, or about 150 million km [93 million mi]) in a spherical cloud known as the Oort Cloud. Comets are best known for the beautiful light they create in the night sky, which results because of ice evaporating from the surface, releasing particles and vapor. The expanding gas and dust produces a spherical cloud around the comet that trails behind it, sometimes for great distances. This release of particles and gas produces streams of meteors that also light up the sky as showers if they enter Earth's atmosphere. One of the most famous comets is Halley's Comet, which is perhaps the best studied of all comets because of a 1986 spacecraft mission to observe it. That expedition found that the comet is a fluffy, porous body with very little strength. In fact, the entire nucleus of Halley's Comet is comprised of only about 20 percent water, and it must therefore consist of 80 percent empty space, which is a network of cracks and voids and loosely cemented materials.[1] Halley's Comet visits the space above Earth approximately once every 76 years, giving every generation a chance to view it (Figure 12.C).

Near-Earth objects, both asteroids and comets, apparently have a relatively short lifetime. As a result, there is a continuous production of these objects because asteroids are continuously kicked out of the asteroid belt, some becoming NEOs. Likewise, comets from the outer solar system have their orbits perturbed by planets or other objects to eventually become NEOs as well.

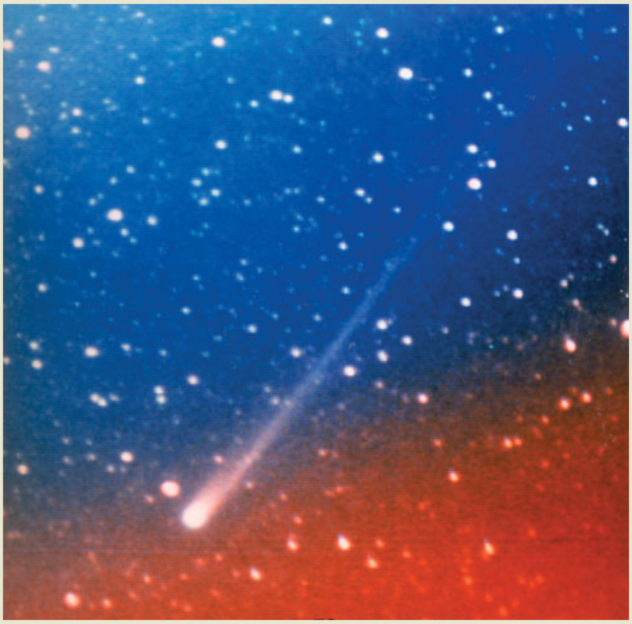


FIGURE 12.C Halley's Comet *(NOAO/AP Photo)*

(Table 12.1). These are relatively slow-moving and can penetrate the atmosphere and produce a serious threat at the surface of Earth. Such bodies produce the Tunguska-type events. Identifying all of these objects will be extremely difficult; there are believed to be about 10 million of them. With a diameter of only 25 m (82 ft), they are relatively small objects, making them difficult to identify and track.[1] It is impossible for us to identify and catalog 10 million small asteroids or comets. We are much better prepared to identify and track objects of a few hundred meters to a kilometer or so in diameter.

Once it has been determined that a large near-Earth object is on a collision path with our planet, options available to avoid or minimize the hazard from an aerial burst or crater-forming event are somewhat limited. In the event of a large comet or asteroid colliding with Earth, there will be no place in which to escape on the planet. Living things, including people, within the blast area will be killed immediately, while those further away are likely to be killed in the ensuing months from the cold and the destruction of the food chain. Even if we could identify and intercept the object, blowing it apart into smaller pieces would likely cause more damage than would one impact from the larger body because each of the smaller pieces would rain on Earth. A more thoughtful approach would be to try to gently divert the object so that it misses Earth. Let's assume that we identify a 400 m (1,300 ft) asteroid that we believe will strike Earth approximately 100 years in the future. In all likelihood, the body has been crossing Earth's orbit for millions of years without an impact. If it were possible to nudge it and change its orbit, it would miss rather than strike Earth. This is not an unlikely scenario. There is a 99 percent probability that we would identify the object at least 100 years before impact. We have the potential technology to change the orbit of a threatening asteroid with small nuclear explosions that are close enough to the asteroid to nudge it but far enough away to avoid breaking it up. Accomplishing this mission would require cooperation among the world's militaries and space agencies. The cost of such an expedition would likely exceed $1 billion. However, this seems a small price to pay, considering the potential damages from a Tunguska-type event if it were to occur in an urban area.

Another option for smaller events might be evacuation. If we could predict precisely where the event would occur months in advance, evacuation is *theoretically* possible. However, evacuating an area of several thousand square kilometers would be a tremendous, if not impossible, undertaking.[1]

In summary, we continue to catalog extraterrestrial objects that intersect Earth's orbit. We are beginning to think about options to minimize the hazard. Given the potential long-term warning before an object would actually strike the surface of Earth, it is very possible that we will be able to devise methods to intercept and minimize the hazard by nudging the object into a different orbit so that it misses Earth.

Making The Connection

Linking the Opening Case History About The Tunguska Event to the Fundamental Concepts

Consider and discuss the following questions:

1. As the human population of Earth increases, how will the risk of a Tunguska event change? Why?
2. Why is the risk of a future impact of a kilometer-scale object so large if such events are very rare?
3. How does the emerging story of past impacts affect how we think about the future over a time period of tens of thousands of years?
4. If the hypothesis that an impact 12,900 years ago significantly disrupted Earth ecosystems and contributed to the mass extinction of large mammals is true, does this require us to think differently about the future of humans?

Summary

Asteroids, meteoroids, and comets are extraterrestrial objects that may intercept Earth's orbit. Small objects may burn up in the atmosphere and be visible as meteors at night. Depending on their size, velocity, and composition, large objects from a few meters to 1,000 km may disintegrate in the upper or lower atmosphere in an aerial burst or may impact the surface of Earth. Large objects can cause local to global catastrophic damage, including mass extinction of life. The best documented impact occurred 65 million years ago (K-T boundary), likely producing the mass extinction of species, including the dinosaurs, recorded in the rock record for that time.

The risk from extraterrestrial aerial burst or direct impact is a function of the probability of an event happening and the consequences if it does occur. Relatively small events such as the 1908 Tunguska explosion will occur somewhere on Earth about every 1,000 years. Seventy percent will occur in or over the oceans. A significantly larger event would be capable of causing catastrophic damage to an urban area. Such events can be expected to occur every few tens of thousands of years. Programs such as Spacewatch and NEAT (Near-Earth Asteroid Tracking) will, with high certainty, identify near-Earth objects of diameters greater than a few hundred meters at least 100 years prior to possible impact. This should allow sufficient time to intercept and divert the object, using nuclear explosions. There are about 10 million smaller objects (potential Tunguska-type objects) that could produce catastrophic damage to urban areas. Identifying all these objects is extremely difficult. Thus we are particularly vulnerable to these smaller objects.

Revisiting Fundamental Concepts

Human Population Growth As our population increases, the potential loss from impact of an extraterrestrial object increases.

Sustainability Sustainability as we know it can be destroyed by impact of a large asteroid.

Earth as a System Earth is a part of the larger solar system. Extraterrestrial processes continue to change our planet, from adding water from comets to changing the landscape and life from impacts of asteroids and comets.

Hazardous Earth Processes, Risk Assessment, and Perception Impact of a large asteroid or comet is the ultimate Earth hazard, capable of causing a mass extinction including humans. The long-term risk is appreciable, but our perception of the hazard is not great as the time between catastrophic events is many millions of years.

Scientific Knowledge and Values Our understanding of our solar system and processes that could impact Earth are better understood than ever before. We place value on this understanding by monitoring the sky to identify potential hazards and forming plans should a threat be identified.

Key Terms

asteroid (p. 404)
comet (p. 404)
meteor (p. 404)
meteorite (p. 407)
meteoroid (p. 404)

Review Questions

1. What is the difference between an asteroid, a meteor, a comet, and a meteoroid?
2. What are the characteristics of an impact crater?
3. Differentiate between a simple crater and a complex crater.
4. What evidence supports the hypothesis of an asteroid impact at the K-T boundary?
5. How is the risk of impact determined?
6. Why was the Tunguska event a wake-up call?

Critical Thinking Questions

1. Describe the likely results if a Tunguska-type event were to occur over or in central North America. If the event were predicted with 100 years' warning, what could be done to mitigate the effects if changing the object's orbit were not possible? Outline a plan to minimize death and destruction.
2. Consider the hypothetical concept of planetary sustainability over a time period of hundreds of millions of years. At this time frame what is the role of large impacts of extraterrestrial objects? How does your answer link to sustainability at the human time frame (hundreds of years)?

Companion Website

www.mygeoscienceplace.com

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

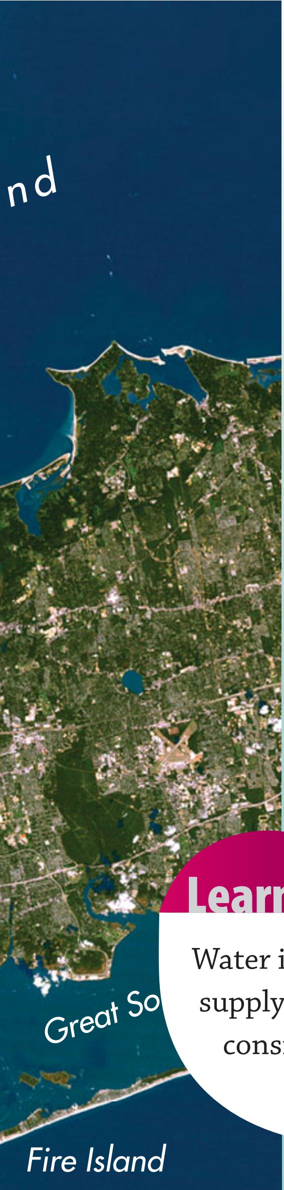
Part 3

Resources and Pollution

People on Earth are absolutely dependent on natural resources associated with the geologic environment, including water (Chapters 13 and 14), minerals (Chapter 15), energy (Chapter 16), and soils (Chapter 17). Our main objective in Part 3 is to present basic information concerning our natural resources and to identify potential environmental problems and solutions associated with the use of resources. Two fundamental certainties come to mind: (1) Earth is the only suitable habitat that we have and (2) our resources are limited. The fact that our resources are limited is true not only for our mineral resources and fossil fuels, which are recognized as nonrenewable, but also for water, trees, and some forms of energy, which are considered renewable. What is renewable or nonrenewable depends on the time frame as well as on our pattern of resource allocation and utilization. Resources we commonly think of as completely renewable, such as water, are really not renewable if the resource is spoiled, used unwisely, or not available when it is needed at a particular location. The nonrenewable/renewable aspect of water resources is particularly true for groundwater, which may take tens to hundreds of years to be replaced by natural processes.

It is important to develop mineral resource utilization and management strategies that will sustain our resources so that future generations will have their fair share. Thus, sustainability is the environmental solution, and it is not a one-size-fits-all situation. That is, the requirement for sustainable water resources is quite different from the requirement for sustaining energy resources, minerals, or our soils. Sustaining nonrenewable resources, such as metals and oil, is not possible because supplies are finite. The best we can do is to conserve and recycle the nonrenewable resources so they can be used as long as possible and so future generations will also have these resources.

High-altitude image of Long Island, New York and surrounding areas where water supply is a growing problem. *(M-Sat Ltd/Photo Researchers, Inc.)*



13

Water Resources

Learning Objectives

Water is one of our most basic resources. Ensuring that we maintain an adequate, safe, sustainable supply of water is one of our most important environmental objectives. In this chapter, we will consider the topics of water supply, use, and management. We will focus on the following learning objectives:

- **Understand the water cycle and the basic concepts associated with our water supply**
- **Understand the main types of water use**
- **Understand basic surface-water and groundwater processes**
- **Be able to discuss some of the key principles associated with water management**
- **Know what wetlands are and understand their environmental significance**
- **Know why we are facing a global water shortage linked to food supply**

Case History

Long Island, New York

The western end of Long Island, part of New York City, is the location of the boroughs of Brooklyn and Queens; it is home to about 4 million people (see image of Long Island opening this chapter). Another 3 million people live in central and eastern Long Island (Nassau and Suffolk Counties). Human population of the island has increased dramatically in the past century. The population of Nassau and Suffolk Counties in 1920 was about 0.25 million; today it is about 3 million, a 12-fold increase.

The coastal eastern end of Long Island in Suffolk County includes the famous Hamptons (**Figure 13.1**), home of affluent coastal communities, state parks, and the Montauk Lighthouse (see the opening case history in Chapter 11). It is a major tourist area. Tourism attracts people and requires seasonal resources. Two important aspects of tourism are water supply and waste management—both topics of concern to any coastal resort.

FIGURE 13.1 Eastern Long Island Aerial view of the Hamptons, eastern Long Island, New York. *(Jupiter Images)*

The topography, geography, and groundwater hydrology of Long Island is the result of late Pleistocene glaciations that were at a maximum about 20,000 years ago. Materials deposited directly by the glaciers or as the glaciers retreated include abundant, thick sand and gravel that soak up the rain and store the water beneath the surface. The highest hill on the island, with an elevation of about 122 m (400 ft), is Jayne's Hill in Suffolk County. The hill is part of a low, linear west-to-east ridge composed of glacial deposits. The largest lake on the island is a kettle lake about 1 km (0.6 mi) wide, known as Ronkonkoma Lake. The lake (also in Suffolk County) formed as the glaciers retreated, leaving blocks of glacial ice that formed depressions that eventually filled with water.

Water supply and pollution have been serious problems on the western end of Long Island since at least the beginning of the twentieth century, and people living there depend on water imported from upstate New York. Nassau and Suffolk counties in the central and eastern end of Long Island (referred to as Long Island proper) do not import water; they depend entirely on groundwater. Those counties carefully monitor their water resources, yet they are experiencing water supply and pollution problems.[1]

Water supply for Nassau and Suffolk Counties is a potential problem because there are several demands for the resource. Groundwater is needed for the activities of the 3 million people who depend on the resource as their only water supply. Water is also needed to maintain ecosystems, such as wetlands, creeks, and ponds.

Groundwater (**Figure 13.2**) in Nassau County is a tremendous resource, with about 500 public water systems and 1,500 wells. Despite a huge quantity of groundwater, intensive pumping in recent years has caused water levels to decline as much as 15 m (50 ft) in some areas. In other words, the groundwater is being mined. Streams that used to

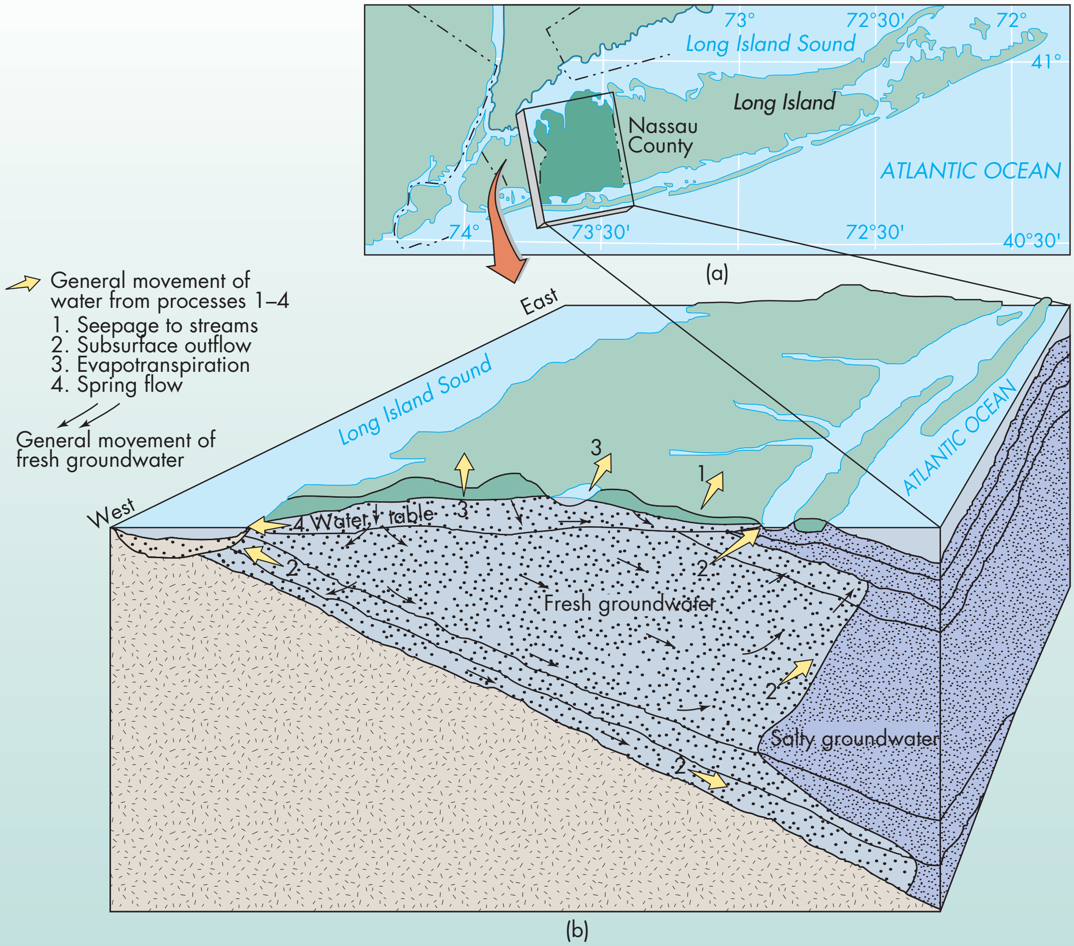


FIGURE 13.2 Groundwater movement at Long Island, New York The general movement of surface and groundwater for Nassau County, Long Island, New York. *(From Alley, W. M., Reilly, T. E., and Franke, O. L. 1999. U.S. Geological Survey Circular 1186)*

flow all year as a result of groundwater seeping into their channels now experience less flow or have dried up and flow only in response to precipitation.[2] The decline in water level has allowed the infiltration of salty groundwater in some locations, a problem known as *salt-water intrusion.* However, the most serious water pollution problem in Nassau County is associated with urbanization. There are many sources of pollution, including urban runoff, household sewage from septic tanks, salt used to de-ice highways, and industrial and other solid waste. These pollutants have a tendency to be released into surface waters and then migrate downward to groundwater resources. It has been noted that the greatest concentrations of pollutants are located beneath densely populated urban areas. Water levels in these areas have dramatically declined, and nitrates from sources such as septic tanks and fertilizers are routinely introduced into the subsurface environment.[1,2] Finally, landfills containing urban waste have been of particular concern because the waste often contains many pollutants that may seep into groundwater resources. Due to past groundwater pollution and potential for future pollution, most landfills on Long Island have been closed.

The ongoing lesson learned from Long Island's groundwater problems is that the need for water resources goes hand in hand with the threat of water pollution. Urban areas are often in need of groundwater resources; at the same time, urban processes are likely to pollute these resources. As human population continues to increase, and more land is developed for agriculture and urban uses on Long Island, the linked problems of water supply and water quality undoubtedly will increase. Water pollution is discussed in detail in Chapter 14.

13.1 Water: A Brief Global Perspective

The global **water cycle**, or *hydrologic cycle*, involves the movement or transfer of water from one of Earth's storage compartments, such as the ocean, lakes, and the atmosphere, to another. In its simplest form, the water cycle can be viewed as water moving from the oceans to the atmosphere, falling from the atmosphere as rain and snow, and then returning to the oceans as surface runoff and subsurface flow or to the atmosphere by evaporation. The cyclic nature of this global movement of water is illustrated in **Figure 13.3**. The major processes are evaporation, precipitation, transpiration (loss of water by plants to the atmosphere), surface runoff, and subsurface groundwater flow. These are quantitatively shown in **Figure 13.4**. The annual volume of water transferred from the ocean to the land is balanced by the same volume returning by river and groundwater flow to the ocean, and there is a balance between total evaporation and precipitation.[2] The water that returns to the ocean is changed because it carries with it gravel, sand, silt, and clay that has eroded from the land. The return flow also carries many chemicals. Most of the chemicals are natural; however, many human-made and human-induced compounds are trapped in the return flow, such as organic waste and nutrients, as well as thousands of chemicals used in agricultural, industrial, and urban processes.

Water is a heterogeneous resource that can be found in liquid, solid, and gaseous forms on or near Earth's surface. Water's residence time may vary from a few days to many thousands of years, depending on its specific location (**Table 13.1**). Furthermore, more than 99 percent of Earth's water is unavailable or unsuitable for beneficial human use, either because of its salinity, as with seawater, or its form and location, as is the case with water stored in ice caps and glaciers. Thus, all people compete for less than 1 percent of Earth's water supply!

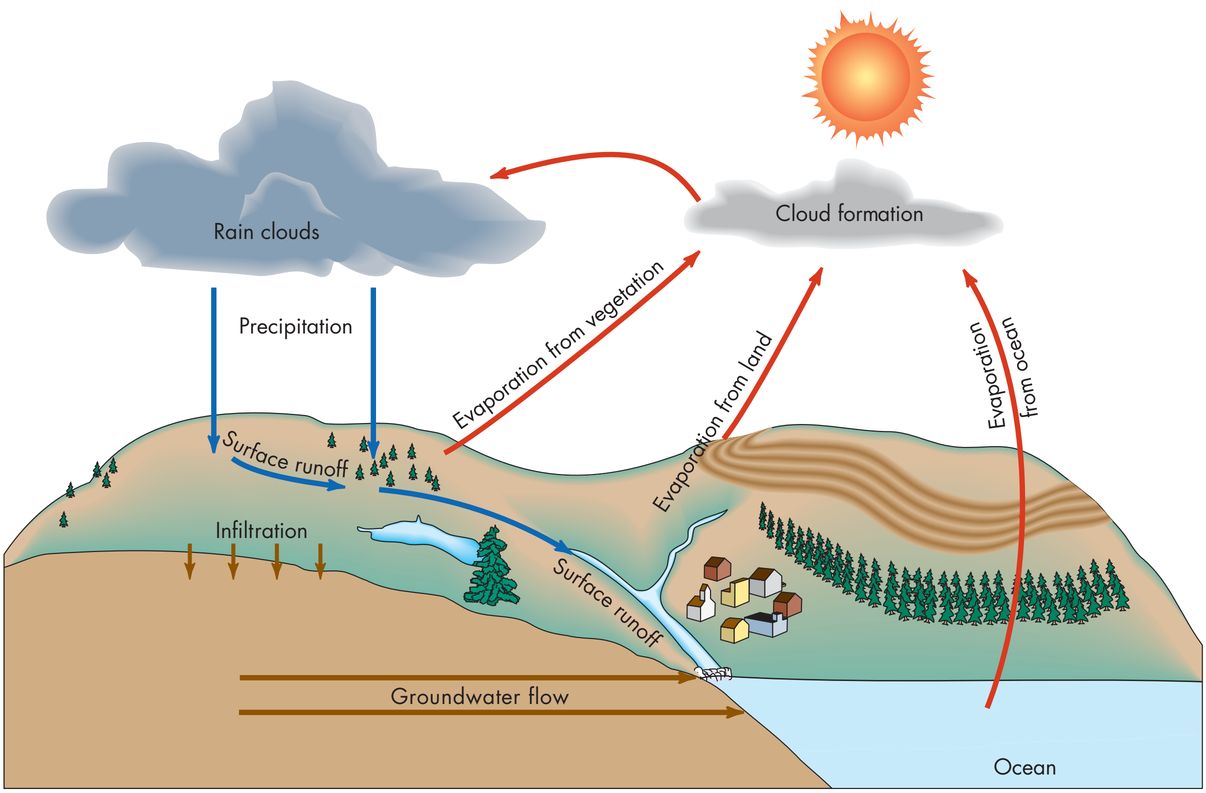
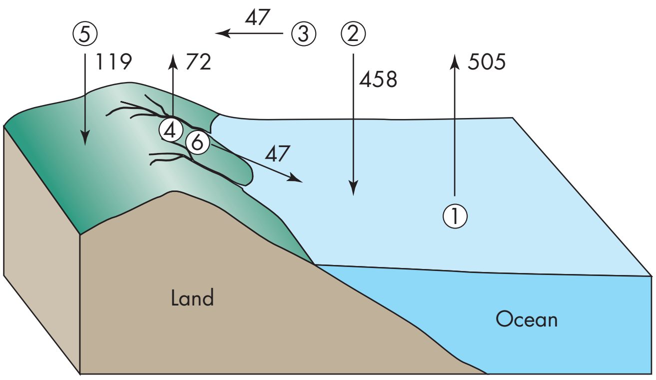


FIGURE 13.3 Hydrologic cycle Idealized diagram showing the hydrologic cycle's important processes and transfer of water. In many areas, winter precipitation is in the form of snow, and spring and summer snowmelt contribute to surface runoff and infiltration of water to enter the groundwater system. *(Modified after Council on Environmental Quality and Department of State. 1980. The Global 2000 Report to the President. Vol. 2)*



Annual flow of water on Earth in thousands of km^3

① Evaporation from oceans to the atmosphere
② Precipitation to oceans
③ Transfer of water from atmosphere to land
④ Evaporation to atmosphere from land
⑤ Precipitation to land
⑥ Runoff of surface water and groundwater from land to oceans

Example of global water balances:

- Water transferred to land from atmosphere ③ = Water returned to ocean ⑥
- Total evaporation ① + ④ = Total precipitation ② + ⑤

FIGURE 13.4 Global transfer of water Movement of water in the global water cycle. Units are thousands of cubic kilometers (km^3) per year. *(Data from Gleick, P. H. 1993. An introduction to global fresh water issues. In* Water in Crisis, *ed. P. H. Gleick, pp. 3–12. New York: Oxford University Press)*

TABLE 13.1 The World's Water Supply (Selected Examples)

Location	Surface Area (km^2)	Water Volume (km^3)	Percentage of Total Water	Estimated Average Residence Time
Oceans	361,000,000	1,230,000,000	97.2	Thousands of years
Atmosphere	510,000,000	12,700	0.001	9 days
Rivers and streams	—	1,200	0.0001	2 weeks
Groundwater; shallow to depth of 0.8 km	130,000,000	4,000,000	0.31	Hundreds to many thousands of years
Lakes (freshwater)	855,000	123,000	0.009	Tens of years
Ice caps and glaciers	28,200,000	28,600,000	2.15	Up to tens of thousands of years and longer

Data from U.S. Geological Survey.

13.2 Surface Water

Surface Runoff and Sediment Yield

Surface runoff has important effects on both the transport of materials and erosion. Surface water can dislodge soil and rock particles on impact (Figure 13.5). Water can move these materials either in a dissolved state or as suspended particles. The number and size of the suspended particles moved by surface waters depend on the volume and depth of the water, as well as the velocity of flow. The faster a stream or river flows, the larger the particles it can move, resulting in more material being transported. Therefore, the factors that affect runoff also affect sediment erosion, transport, and deposition.

The flow of water on land is divided into watersheds. A **drainage basin**, or **watershed**, is an area of

(a)

(b)

FIGURE 13.5 Soil erosion (a) A raindrop falling on soil causes soil particles to be lifted into the air, initiating the erosion process. Raindrops vary in diameter from about 0.5 mm to 5 mm (average about 2 mm). They form from condensation around a particle of dust, smoke or salt. The diameter of the splash may be several times that of the raindrop. The velocity of an average raindrop at impact is about 6 m/sec, on impact soil particles may be ejected by a large raindrop to a height of about 1 m and 1.5 m to the side. *(Superstock)* (b) Surface runoff often causes the formation of small gullies such as those shown here. *(Courtesy of U.S. Department of Agriculture)*

land that contributes water to a particular stream or river. A drainage basin is a basic unit of the landscape. **Figure 13.6** shows two side-by-side drainage basins (A and B) with similar geology. The boundary between them is called a *drainage divide*.

Large drainage basins can be subdivided into smaller ones. For example, the Mississippi River drainage basin drains about 40 percent of the United States but contains many subbasins, such as the Ohio and Missouri basins. Drainage basins, such as the Ohio, may be further divided into smaller basins. Two drops of rain separated by only

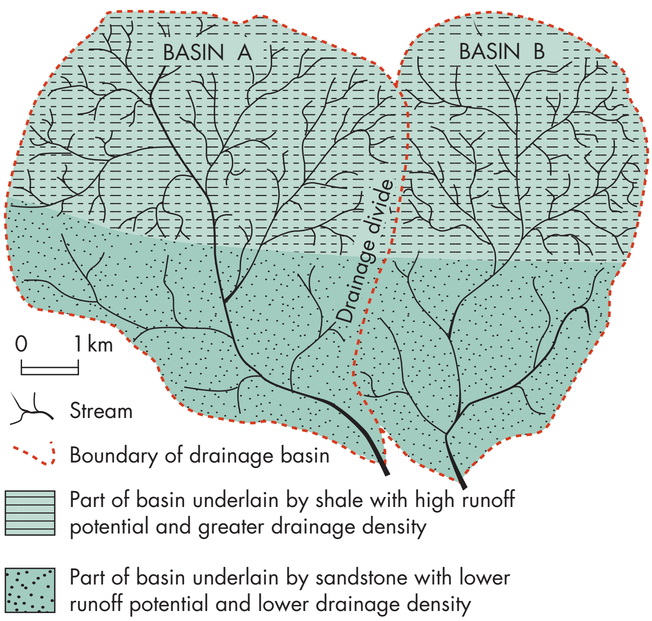


FIGURE 13.6 Two drainage basins Water falling on one side of the central boundary will drain into basin A; on the other side, water will drain into basin B. The two drainage basins have similar geology, consisting of shale and sandstone.

centimeters on a continental divide, which is a large-scale drainage divide from each side of which river systems flow in opposite directions, may end up a few weeks later in different oceans, thousands of kilometers apart. We may also think of a drainage basin as the land area that contributes its runoff to a specific *drainage net*, which is the set of channels that makes up a drainage basin. The drainage net in basin A in Figure 13.6 includes all the channels from the small headwater streams at the top of the drainage basin to the single large channel at the bottom of the drainage basin. Thus, the term *drainage basin* refers to an area of land, whereas the term *drainage net* refers to the actual river and stream channels in the drainage basin.

Factors Affecting Runoff and Sediment Yield

The amount of surface-water runoff and sediment carried by the runoff varies significantly among drainage basins and rivers. The variation results from geologic, topographic, climatic, vegetation, and land-use characteristics of a particular drainage basin, as well as changes in these factors over time. Even the most casual observer can see the difference in the amount of sediment carried by the same river in flood state and at low flow, since floodwaters are usually muddier.

Geologic Factors. The major geologic factors affecting surface-water runoff and sedimentation include rock and soil type, mineralogy, degree of weathering, and structural characteristics of the soil and rock. Fine-grained, dense clay soils on shale and exposed rock types with few fractures generally allow little water to move downward and become part of the subsurface flow. The runoff from precipitation falling on such materials is comparatively rapid, and there are usually many streams. Conversely, sandy soils on sandstone and well-fractured rocks absorb a larger amount of precipitation and have less surface runoff and fewer streams. These principles are illustrated in Figure 13.6. The upper parts of basins A and B are underlain by shale, and the lower parts are underlain by sandstone. Because the shale has a greater potential to produce runoff than the more porous sandstone, the *drainage density*—that is, the length of stream channel per unit area—is much greater in the shale areas than in the sandstone areas. The drainage density for any area of land is determined by measuring the total length of stream channel from all streams in the area and dividing this length by the area.

Topographic Factors. *Relief* refers to the difference in elevation between the highest and lowest points of any landform of interest. The greater the relief of a drainage basin, the more likely the streams in the basin are to have a steep gradient and a high percentage of steep, sloping land adjacent to the channel. Relief and slope are important because they affect the velocity of water in a stream, the rate at which water infiltrates the soil or rock, and the rate of overland flow. These characteristics then affect the rate at which surface and subsurface runoff enters a stream.

Climatic Factors. Climatic factors affecting runoff and sediment transport include seasonal and annual to longer patterns of precipitation. In general, production of large volumes of water and sediment is associated with infrequent high-magnitude storms that occur on steep, unstable topography underlain by soil and rocks with a high erosion potential.

Vegetation Factors. Vegetation can influence runoff and sediment yield. Vegetation is capable of affecting streamflow in several ways:

- Vegetation may decrease runoff by increasing the amount of rainfall intercepted and removed by evaporation.
- Decrease or loss of vegetation due to climatic change, wildfire, or land use, such as grazing by sheep, will increase runoff or production of sediment or both (**Figure 13.7**).
- Streamside vegetation reduces stream-bank erosion because its roots bind and hold soil particles in place.
- In forested watersheds, large woody debris, such as stems and pieces of wood, may profoundly affect the stream-channel form and processes. In steep mountain watersheds, many of the pool environments that are important for fish habitats may be produced by large woody debris (**Figure 13.8**).

(a)

(b)

FIGURE 13.7 Wildfire and overgrazing increase soil erosion (a) Vegetation loss by wildfire in Southern California in 2009. Runoff and soil erosion may increase several times in the first year or so following wildfire *(Edward A. Keller)*. (b) Grazing of sheep (here in South Africa) can increase runoff, resulting in soil erosion. *(Nigel J. Dennis/Photo Researchers, Inc.)*

FIGURE 13.8 Large woody debris in streams This large redwood stem in Prairie Creek, California, is responsible for the development of a scour pool important in providing fish habitat for the stream ecosystem. Such large woody debris may reside in the stream channel for centuries. *(Charles A. Lauzy)*

Land-Use Factors. Agriculture and urban development are land uses that have an effect on runoff and sediment yield. Agriculture generally increases runoff and sediment yield as land is plowed for crops (see Chapter 17). Urbanization, with construction of streets, parking lots, and buildings for homes and industry, may also greatly increase runoff because of the large amount of impervious pavement covering the land (see Chapters 9 and 17).

13.3 Groundwater

The major source of groundwater is precipitation that infiltrates the surface of the land and goes into soil and rock. The two major zones of groundwater are the *vadose zone* and the *zone of saturation* (Figure 13.9). The vadose zone includes the Earth material above the *water table* which is the boundary between the two zones, including soil, alluvium, and rock. The vadose zone is seldom saturated. The vadose zone was previously called the *unsaturated zone*, but we now know that some saturated areas may exist there at times, as water moves through after precipitation events. The vadose zone has special significance because potential pollutants infiltrating at the surface must percolate through the vadose zone before they enter the saturated zone below the water table. Thus, during environmental subsurface monitoring, the vadose zone is an early warning area for potential pollution to groundwater resources.

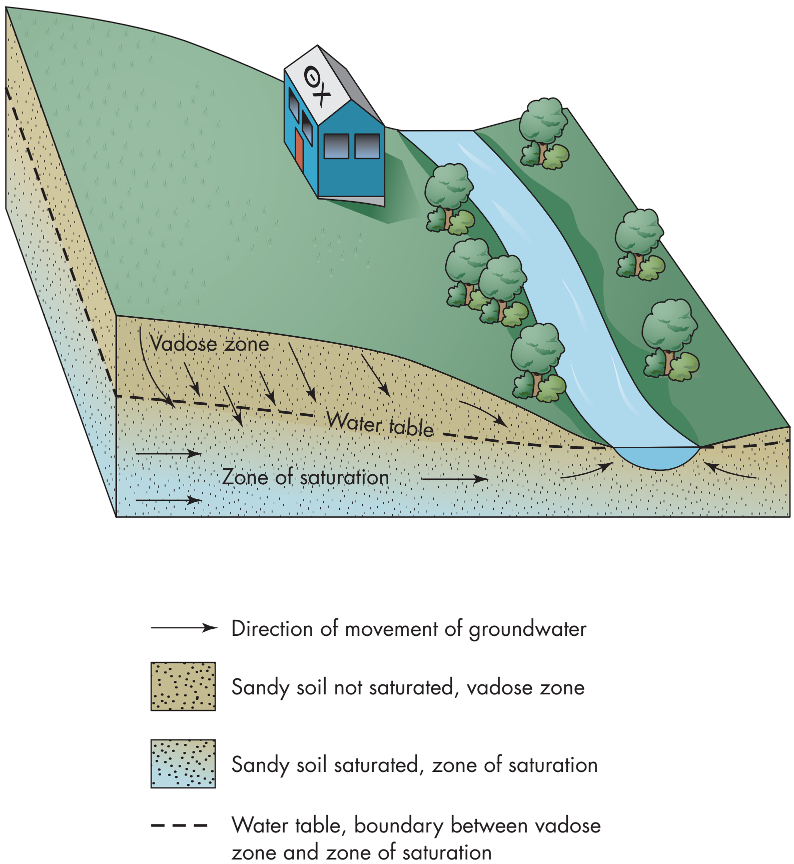


FIGURE 13.9 Groundwater zones Idealized diagram showing the two main zones of groundwater: vadose zone and zone of saturation. Also shown are the water table and directions of groundwater movement.

Water that reaches the zone of saturation begins with infiltration from the surface. Factors that influence the rate of infiltration include:

- **Topography:** With steeper topography, more water runs off, which reduces infiltration.
- **Soil and rock type:** Soils and rocks with lots of open space due to fractures or pore spaces between grains have higher infiltration rates.
- **Amount and intensity of precipitation:** Low-intensity precipitation or snowmelt favors infiltration. High-intensity precipitation favors runoff.
- **Vegetation:** Leaves and stems intercept precipitation. The water then falls more gently to the ground and infiltration increases.
- **Land use:** Urban lands with pavement or roofs reduce infiltration. Agricultural practices generally increase surface runoff and soil erosion, decreasing infiltration. Harvesting of timber, particularly clear-cut logging, reduces vegetation cover, increasing soil erosion and runoff while decreasing infiltration.

Water that percolates through the vadose zone will enter the zone of saturation, where true groundwater flow occurs. As the name implies, the Earth material in the zone of saturation has all of the spaces between grains in soil and rock filled with water—this is the definition of *saturated*. The upper surface of the zone of saturation is the water table.

Aquifers

Earth material capable of supplying groundwater at a useful rate from a well is called an **aquifer** (Figure 13.10). Gravel, sand, soils, and fractured sandstone, as well as granite and metamorphic rocks with high porosity from open fractures, are good aquifers if groundwater is present. A *confining layer* (such as a clay or shale layer) restricts or blocks the movement of groundwater.

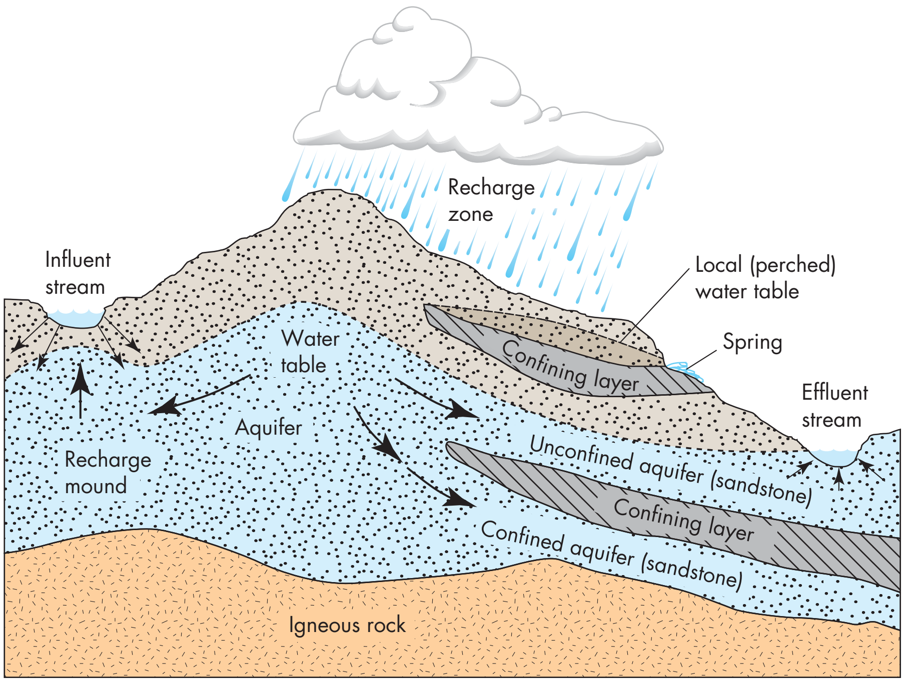


FIGURE 13.10 Groundwater process, showing confined and unconfined aquifers, recharge zone, recharge mound, spring, perched water, and influent and effluent streams.

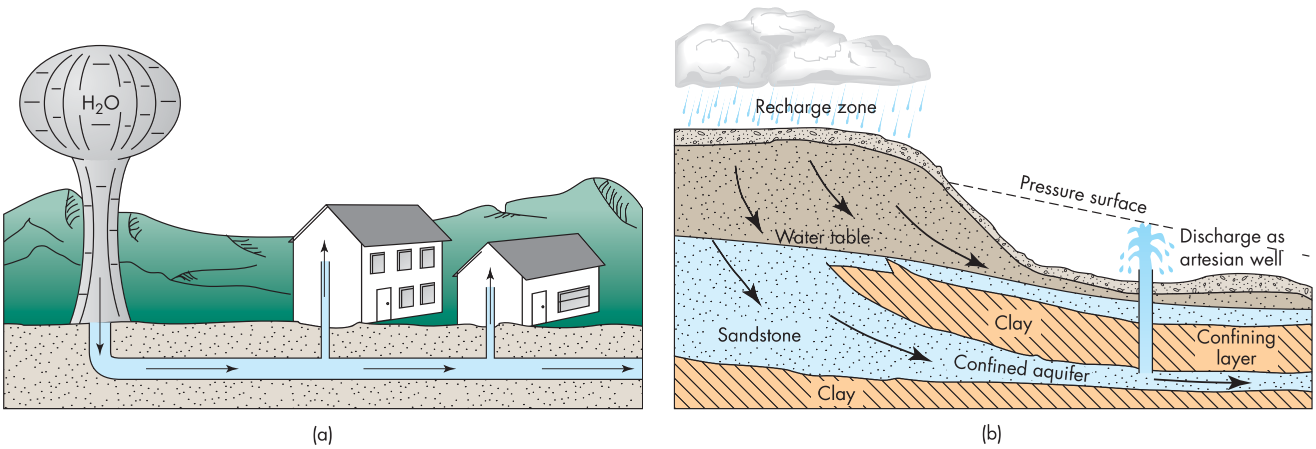


FIGURE 13.11 Development of an artesian well system (a) Water rises in homes because of pressure created by the water level in the tower. If there is only a small amount of friction in the pipes, there will be little drop in pressure. (b) The pressure surface, or water table, in natural systems declines away from the source because of friction in the flow system, but water may still rise above the surface of the ground if impervious particles, such as clay, create a confining layer and cap the groundwater.

An aquifer is called an *unconfined aquifer* if there is no confining layer restricting the upper surface of the zone of saturation at the water table (**Figure 13.10**). If a confining layer is present, the aquifer is called a *confined aquifer*; both confined and unconfined aquifers can be found within the same area. A *perched aquifer* is a local zone of saturation above a regional water table.

The water beneath a confined aquifer may be under pressure, forming *artesian* conditions. Artesian conditions are analogous in their effect to a water tower that produces water pressure for homes (**Figure 13.11a**). Groundwater in an artesian system (Figure 13.11b) moves downward and laterally. It is confined and under pressure. The water may rise upward through rock fractures to form an artesian

spring. The resultant rise may also create an *artesian well* (Figure 13.11b).

In a general sense, *groundwater recharge* is any process that adds water to the aquifer. Groundwater recharge can result from natural processes, most commonly precipitation (Figure 13.10) infiltrating the ground. There is also human-induced infiltration, as, for example, groundwater recharge from leakage and infiltration of water from a broken water line, leakage from a canal, or irrigation of crops. Finally, recharge may be deliberate through the process of *artificial recharge* where surface water from a river or other source is spread on recharge basins to infiltrate into the subsurface to augment the groundwater resource. *Groundwater discharge* is any process that removes groundwater from an aquifer. Natural discharge from a spring is an example of groundwater discharge. A *spring* forms when water flowing in an aquifer intersects Earth's surface. Spring discharge can form the beginning of a stream or river (**Figure 13.12**). Groundwater discharge also occurs when water is pumped from a well.

When water is pumped from a well, a *cone of depression* forms in the water table or artesian pressure surface (**Figure 13.13**). A large cone of depression can alter the direction of groundwater movement within an area. Overpumping an aquifer causes the water table to drop deeper within Earth. This drop necessitates lowering the pump settings or drilling deeper wells. These adjustments are often costly, and they may not work, depending on the hydrologic conditions. For instance, continued deepening to correct for overpumping of wells that tap igneous and metamorphic rocks is limited. Water from these wells is pumped from open fracture systems that tend to close or diminish in number and size with increasing depth. Also, the quality of groundwater may be degraded if it is extracted from deeper water containing more dissolved minerals.

FIGURE 13.12 Spring Discharge of groundwater from Fern Spring at the southern end of Yosemite Valley, California. This spring emerges at the base of a hill slope, as do many other springs. The small stream emerging from the spring pool in a short cascade or falls is about 2 m (6.6 ft) wide. *(Edward A. Keller)*

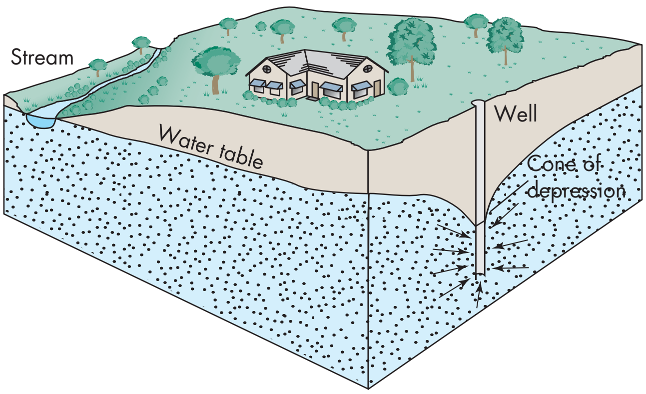


FIGURE 13.13 Pumping groundwater Cone of depression in the water table, resulting from pumping water from a well.

Groundwater Movement

The rate and direction of groundwater movement in an aquifer in part depend on both the gradient of the water table, or *hydraulic gradient*, and the type of material found in the aquifer. In general, the hydraulic gradient for an unconfined aquifer is approximately the slope of the water table. The ability of a particular material to allow water to move through it is called its *hydraulic conductivity*, which is expressed in units of cubic meters (m^3) of water per day through a cross section of 1 m^2—that is, (m^3/day/m^2), which reduces to meters per day. Hydraulic conductivity is, in part, dependent upon the size of the open spaces between grains in an aquifer and how well they are connected. The percentage of empty space, called *void space*, in sediment or rock is called *porosity*. It varies from 1 percent for granite with few fractures to 50 percent for clay. Values of porosity and hydraulic conductivity for selected Earth materials are listed in **Table 13.2**. Notice that some of the most porous materials, such as clay, have low hydraulic conductivity. Its conductivity is low because the spaces between clay particles are very small and hold water tenaciously. Sand and gravel have high porosity, with relatively large openings between grains and a high hydraulic conductivity. These relations explain why sand and gravel form aquifers, and clay forms aquitards. Groundwater moves rapidly in sands and very slowly in clays. The rate of flow of groundwater is directly proportional to the product of the hydraulic gradient and the hydraulic conductivity in a famous equation known as **Darcy's law**. Using Darcy's law to express the quantitative relationship of hydraulic gradient and hydraulic conductivity to groundwater flow allows us to solve many problems, such as the rate of groundwater flow and how fast groundwater is being used or replenished. Darcy's law is discussed further in Appendix E, where an example of groundwater movement is presented.

Groundwater Supply

Nearly half the population of the United States uses groundwater as a primary source of drinking water. Therefore, protecting groundwater resources is an environmental problem of particular public concern. Fortunately, the total amount of groundwater available in the United States is enormous. Within the contiguous United States, the amount of groundwater within 0.8 km (0.5 mi) of the land surface is estimated to be 125,000 to 224,000 km^3 (30,000 to 54,000 mi^3). Put in perspective, the lower estimate is about equal to the total flow of the Mississippi River during the past 200 years. Unfortunately, the cost of water pumping and exploration reduces the total quantity of groundwater that is available.[3]

In many parts of the country, groundwater withdrawal from wells exceeds natural inflow or recharge. In such cases, water is being "mined" and can be considered a nonrenewable resource. Groundwater overdraft is a serious problem in the Texas–Oklahoma–High Plains areas, California, Arizona, Nevada, New Mexico, and isolated areas of Louisiana, Mississippi, Arkansas, and the South Atlantic–Gulf region (**Figure 13.14a**). In

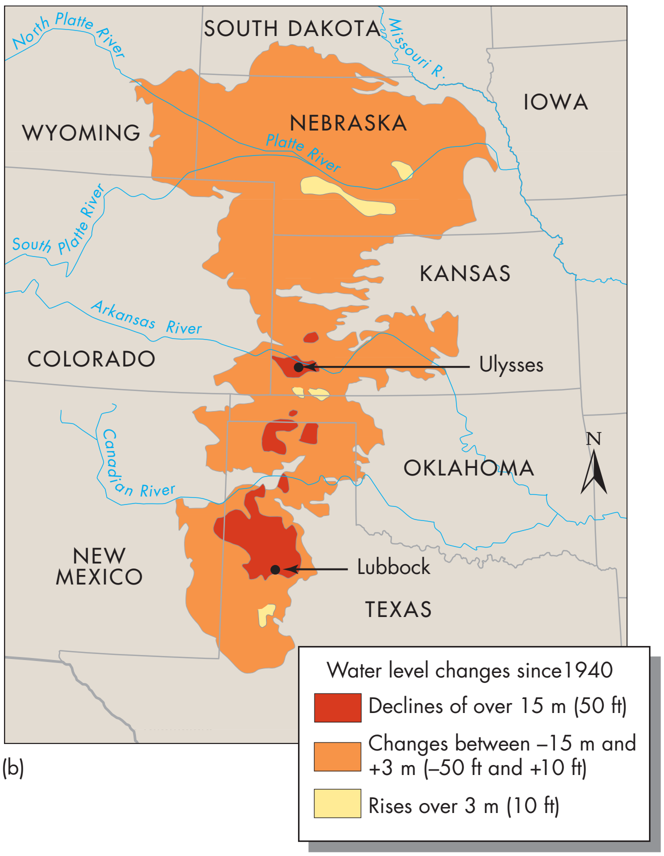
TABLE 13.2 Porosity and Hydraulic Conductivity of Selected Earth Materials

	Material	Porosity (%)	Hydraulic Conductivity[1] (m/day)
Unconsolidated	Clay	50	0.041
	Sand	35	32.8
	Gravel	25	205.0
	Gravel and sand	20	82.0
Rock	Sandstone	15	28.7
	Dense limestone or shale	5	0.041
	Granite	1	0.0041

[1] In older works, may be called *coefficients of permeability*.

Modified after Linsley, Kohler, and Paulhus, 1958. *Hydrology for Engineers*. New York: McGraw-Hill. Copyright © 1958 by McGraw-Hill Book Company. Used by permission of McGraw-Hill Book Company.

(a)



(b)

FIGURE 13.14 Mining groundwater (a) Groundwater overdraft for the contiguous United States. (b) A detail of water level changes in the Ogallala aquifer, Texas–Oklahoma–High Plains area. Ulysses, Kansas, and Lubbock, Texas, are two communities located where declines in groundwater are most severe. Both are facing urban water supply problems. *(U.S. Geological Survey)*

the Texas–Oklahoma–High Plains area alone, the overdraft is approximately equal to the natural flow of the Colorado River.[4] The Ogallala aquifer, composed of water-bearing sands and gravel, underlies this region from South Dakota into Texas (Figure 13.14b). Although the aquifer holds a tremendous amount of groundwater, it is being used in some areas at a rate that is up to 20 times that of natural recharge by precipitation infiltration. The water level in many parts of the aquifer has declined in recent years, and, eventually, a significant portion of land now being irrigated may return to dry farming if the resource is depleted.

Some towns and cities in the High Plains also have water supply problems. Along the Platt River in northern Kansas, groundwater levels are still high, and there is enough water for now (Figure 13.14). Further south, in southwest Kansas and the panhandle in western Texas where water levels have declined the most, supplies may last only another decade or so. The situation for urban water in Ulysses, Kansas (population 6,000), and Lubbock, Texas (population 200,000), is becoming a problem. South of Ulysses, Lower Cimerron Springs, which was a famous water hole along a dry part of the Santa Fe Trail, dried up decades ago due to pumping groundwater, a symptom of what was to come. Both Ulysses and Lubbock are now facing water shortages and will need to spend millions of dollars to find alternative sources.

To date, only a few percent of the total U.S. groundwater resource has been depleted, but water levels are declining in parts of Kansas, Oklahoma, New Mexico, and Texas. As the water table becomes lower, yields from wells decrease, and energy costs to pump the water increase. More than half a century of irrigation in the High Plains area and Ogallala aquifer has created the water problems seen in these areas.

13.4 Interactions Between Surface Water and Groundwater

Surface Water and Groundwater

Surface water and groundwater are so interrelated that we need to consider the two as part of the same resource.[5] Some linkages between surface water and groundwater are shown in **Figure 13.15**. Surface

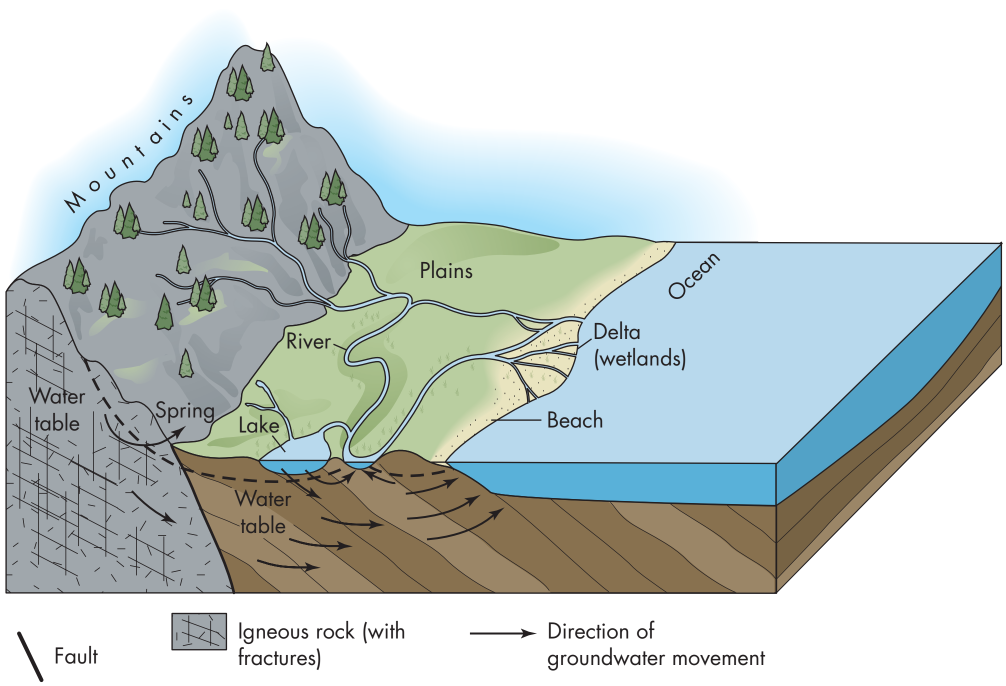


FIGURE 13.15 Surface water–groundwater interactions Idealized diagram showing some of the ways surface water and groundwater interact in the landscape from the mountains to the sea. For example, groundwater moves up along the fault to discharge as a spring and then seeps into lakes and rivers on the plains, delta and beaches, and offshore into the ocean.

water infiltrates from the lake to groundwater, river flow receives groundwater seepage, and groundwater at the coast comes to the surface in wetlands and seeps into the oceans.

Nearly all natural surface-water environments, such as rivers, lakes, and wetlands, as well as human-constructed water environments, such as reservoirs, have strong linkages with groundwater. Withdrawal of groundwater by pumping from wells can reduce streamflow, lower lake level, and reduce water in wetlands. Conversely, withdrawal of surface water can deplete groundwater resources. As a result, groundwater management requires that the linkages between surface water and groundwater be known and understood.[5]

Figure 13.10 shows some of the interactions between surface water and groundwater. In particular, two types of streams may be defined. *Effluent streams* tend to be perennial—that is, to flow all year. During the dry season, groundwater seeps into the channel, maintaining streamflow (Figure 13.10, right). *Influent streams* are often above the water table everywhere along their channel and flow only in direct response to precipitation. Water from influent streams moves down through the vadose zone to the water table, forming a recharge mound (Figure 13.10, left). Influent streams may be intermittent or ephemeral, in that they flow only part of the year.

From an environmental standpoint, influent streams are particularly important because water pollution in the stream may move downward through the streambed and eventually pollute the groundwater below. Dry river beds are particularly likely to experience this type of problem. For example, the Mojave River in the desert of southern California is dry most of the time in the vicinity of Barstow. The river bottom was the site of a railroad yard where trains and other equipment were cleaned with solvents. These solvents infiltrated down through the vadose zone and contaminated groundwater used by several communities for drinking and other municipal purposes.

Karst. Some of the most interesting interrelationships between surface water and groundwater occur in areas underlain by soluble rocks, such as limestone. Often the limestone is dense, thin bedded, and well jointed and has an abundance of fractures. A particular type of topography can result from this type of limestone that is the result of the diversion of surface waters to subterranean routes. Known as **karst topography**, these regions are very common in the United States, where approximately 25 percent of the surface land area is underlain by limestone. The land surface in karst areas is often dotted with pits formed by chemical weathering, known as *sinkholes*, that vary in size from one to several hundred meters in diameter. Sinkholes can result from one of two processes: (1) solutional weathering at the surface of the limestone, with water diverted to subterranean routes below the sinkhole, or (2) pits produced by collapse of surface material into part of an underground cavern system, forming spectacular collapse sinkholes (**Figure 13.16**). The dissolution of limestone is a chemical weathering process, and limestone is particularly susceptible to chemical weathering from acids commonly found in the natural environment (see A Closer Look: Weathering in Chapter 3). As solutional pits enlarge and water moves downward through limestone, a series of caverns may be produced. The pockmarked surface of a karst area resulting from sinkhole development often forms a *karst plain*. The Mitchell Plain in southern Indiana, shown in **Figure 13.17**, is an example of a karst plain. Because limestone is so abundant, all states in the contiguous United States have some karst features; Carlsbad Caverns in southeastern New Mexico is a spectacular example. Major belts of karst topography in the United States are (1) a region

FIGURE 13.16 Collapsed sinkhole Golly Hole, Alabama. *(Geological Survey of Alabama)*

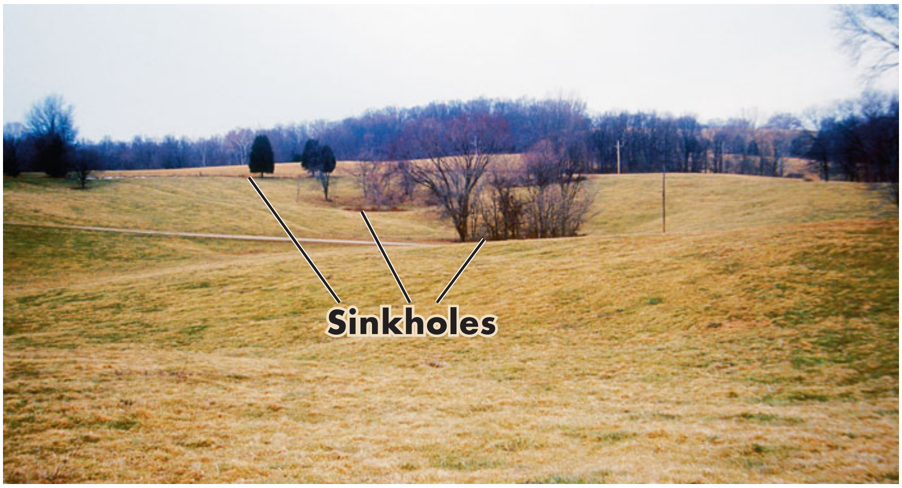


FIGURE 13.17 The Mitchell karst plateau This plateau in southern Indiana has numerous sinkholes. *(Samuel S. Frushour, Indiana Geological Survey)*

extending through the states of Tennessee, Virginia, Maryland, and Pennsylvania; (2) south-central Indiana and west-central Kentucky; (3) the Salem–Springfield plateaus of Missouri; (4) central Texas; and (5) central Florida. One of the most famous cave systems in the United States is Mammoth Cave in Kentucky. Substantial research has been dedicated to explaining the origin of caverns and their development through time. It is clear that groundwater moving through rocks is the primary mechanism that forms caves. Cavern systems tend to form at or near the present water table where there is a continuous replenishment of water that is not saturated with the weathering products of the limestone. However, because many cavern systems contain a number of levels, it is believed that each level may represent a different time of cave formation and, thus, may be related to a fluctuating water table. Fundamentally, caves are enlarged as groundwater moves through limestone along bedding plains or fractures, eventually forming a cavern. Later, if the water table moves to a lower level, water seeping into the cavern starts to deposit calcium carbonate on the sides, floor, and ceiling, forming the beautiful cave formations such as *flowstone*, *stalagmites*, and *stalactites* (Figure 13.18).

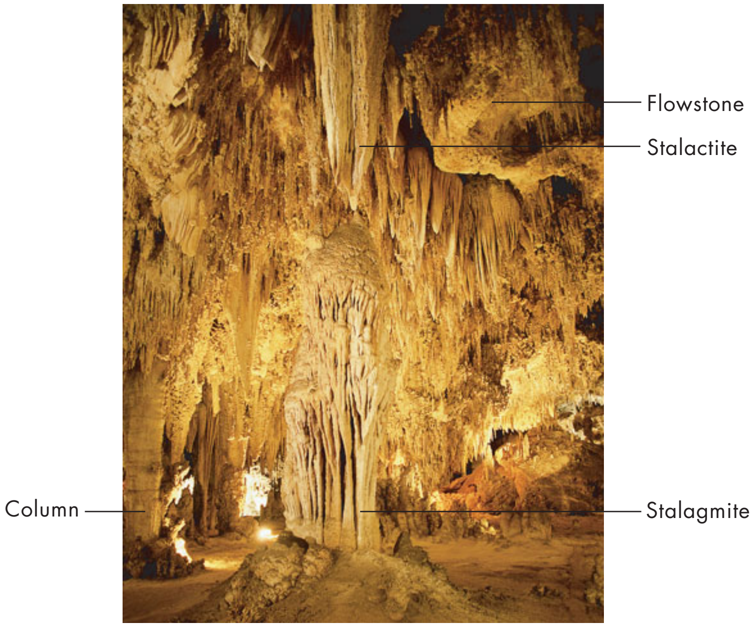


FIGURE 13.18 Cave formations in Carlsbad Caverns, New Mexico These formations include stalactites, which hang from the ceiling; stalagmites, which grow up from the ground; and flowstone, which forms as water slowly flows down the walls or across an incline. The term *stalagmite* has a letter *g* in it to remind us it forms from the ground up. *(Bruce Roberts/Photo Researchers, Inc.)*

From an environmental perspective, karst topography causes many problems, including the following:

- Water pollution occurs where sinkholes have been used for waste disposal. The bottom of many sinkholes is near the water table; this proximity directly injects water pollutants into the groundwater system.
- Cavern systems are prone to collapse, producing sinkholes that may form and damage

buildings on the ground surface, roads, and other facilities (see Chapter 10).

- In many areas underlain by limestone, such as the Edwards Plateau in Texas, groundwater is being mined. As a result of the mining, important karst springs where water emerges from caverns are being changed; the springs are experiencing less discharge or may dry up completely. These changes have important ecological consequences because many of these springs harbor forms of life unique to the spring environment. Their loss causes a reduction in biodiversity and contributes to the increasing number of endangered species (see Case History: The Edwards Aquifer, Texas—Water Resource in Conflict).

13.5 Desalination

Desalination of seawater occurs at about 15,000 plants around the world. The salt content must be significantly reduced for the water to be drinkable, or *potable*. Large desalination plants produce water that costs several times that paid for traditional water supplies. Because the various processes that actually remove the salt require energy, the cost of the water is tied to increasing energy costs. New technology has greatly reduced the energy requirements to desalinate water. As a result, the use of desalinated water will certainly increase, especially as more traditional sources of water are stressed.

13.6 Water Use

To discuss water use, we must distinguish between offstream uses and instream uses. **Offstream use** is water that is removed or diverted from its source. Examples include water for irrigation, thermoelectric power generation, industrial processes, and public supply. **Consumptive use** is a type of offstream use in which water does not return to the stream or groundwater resource immediately after use. This is the water that evaporates, is incorporated into crops or products, or is consumed by animals and humans.[4,8] In **instream use**, the water that is used is not withdrawn from its source. Examples include use of river water for navigation of vessels, hydroelectric power generation, fish and wildlife habitats, and recreation.

Multiple instream uses of rivers and streams usually create controversy because each use requires different conditions to prevent damage or detrimental effects. Fish and wildlife require seasonal fluctuations in water levels and flow rates for maximum biological productivity, and these levels and rates differ from the requirements for hydroelectric power generation, which requires large daily fluctuations in discharges to match power needs. Similarly, both of these may conflict with requirements for shipping and boating. The discharge necessary to move the sediment load in a river may require yet another pattern of flow. Figure 13.19 illustrates the seasonal patterns of discharge for some of these uses.

Movement of Water to People

In our modern civilization, water is often moved vast distances from areas with abundant rainfall to areas of high usage. In California, demands are made on northern rivers for reservoir systems to supply the cities in the southern part of the state. Two-thirds of California's runoff occurs north of San Francisco, where there is a surplus of water,

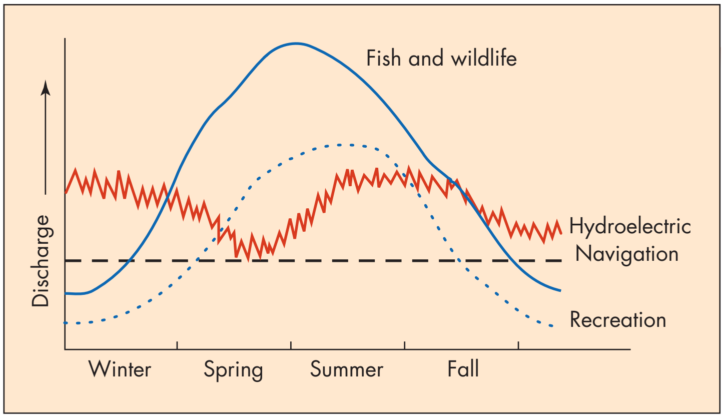


FIGURE 13.19 Various uses of water in a river are in conflict Diagram comparing instream water uses and the varying discharges for each use. Discharge is the amount of water passing by a particular location and is measured in cubic meters per second (cms). The zigzag pattern for hydroelectric use results from rapid (often daily) change in water released from a dam to produce electric power. Larger seasonal changes reflect winter and summer power demands for heating and air conditioning. The "flat line" hydrograph is preferred for boat or barge traffic.

Case History

The Edwards Aquifer, Texas—Water Resource in Conflict

Mark Twain wrote, "Whisky is for drinking and water is for fighting over." In central Texas, the Edwards aquifer, a karst flow system developed in limestone, has created an intense conflict over water. The conflict has escalated into nearly open warfare from a legal, political, and economic viewpoint.[6]

The geology of the Edwards aquifer is interesting. Water that recharges the aquifer is primarily from streamflow over the aquifer, except where it is confined by layers of clay beds and shales. The combination of geologic structures, including folds and a zone of normal faulting, along with the karst flow system, results in a complex aquifer with points of natural discharge at major karst springs (**Figure 13.A**). These springs exemplify the conflicting interest in water resources. For example, the Barton Springs Swimming Pool in Austin, Texas, is supplied by water that discharges from submerged openings in fractured limestone, visible on the right bank in **Figure 13.B**. In addition to providing important areas for recreation, Barton Springs is the only environment for the endangered Barton Springs salamander. The city of Austin dramatically illustrates conflicts between increasing urbanization and water resources. How can Texans continue to maintain a quality environment in the face of increasing water demands from cities such as Austin and San Antonio? It is clear that future decisions concerning the use of the Edwards aquifer and its abundant water resources will have significant social, economic, and environmental ramifications. In order to make these decisions, decision makers will have to conduct an accurate hydrogeologic evaluation of the entire aquifer system in order to determine how its waters may be allocated to the various users without degrading environmental systems.

The Edwards aquifer is one of the most prolific in North America. It provides water for more than 2 million people, including almost all the water used by the city of San Antonio and many smaller municipalities,

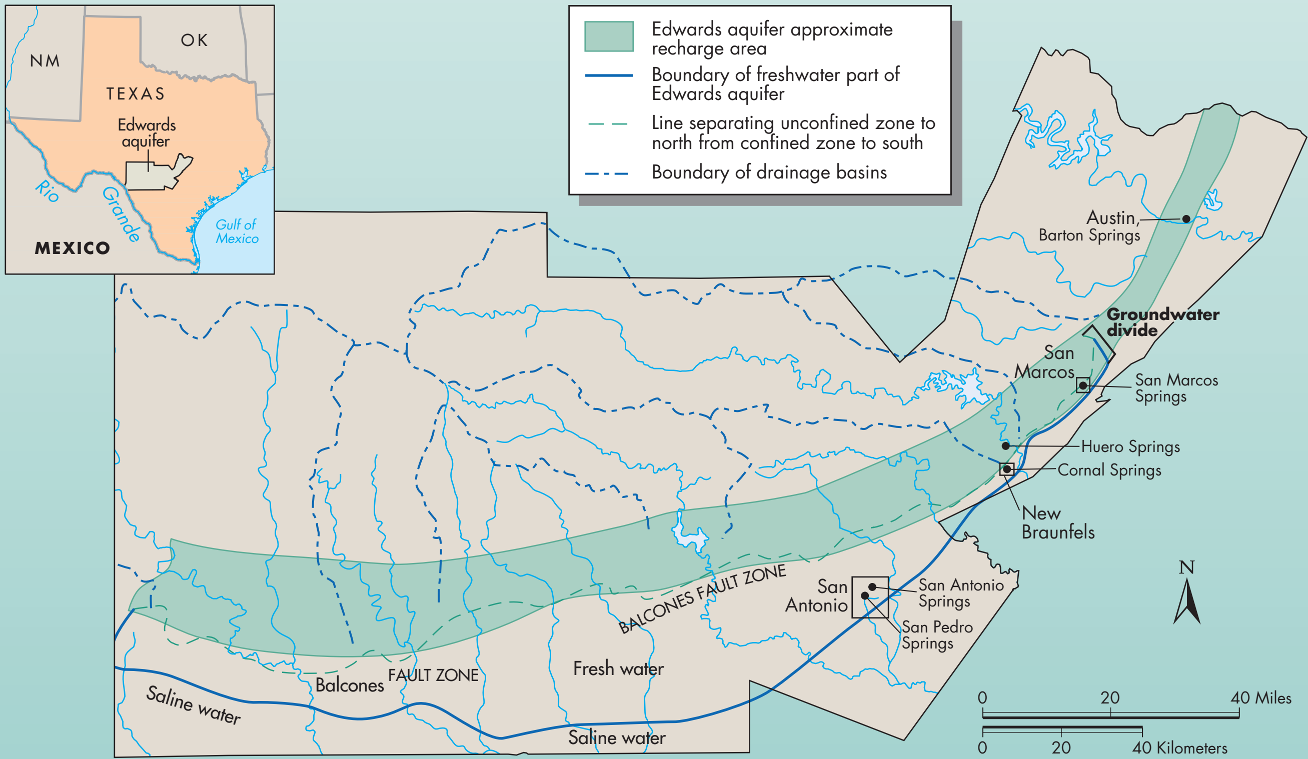


FIGURE 13.A Edwards aquifer, Texas This diagram shows the location of the recharge area and major springs. *(Modified and simplified after Loaiciga, H. A., Maidment, D. R., and Valdes, J. B. 1999. Climate-change impacts in a regional karst aquifer, Texas, USA.* Journal of Hydrology *227:173–194)*

FIGURE 13.B Barton (karst) spring Near Austin, Texas. *(Marshall Frech)*

industries, and agriculture. Water yields from a single well in the aquifer can be incredibly high. A well drilled in 1991 was one of the world's largest. It flowed without pumping with a natural yield of 25,000 gallons per minute—enough to fill a good-sized backyard swimming pool.[7]

The Edwards aquifer is recharged primarily through influent streams that flow over the recharge zone where water sinks into the limestone (Figure 13.A). The recharge is dependent on the duration and volume of streamflows. The rate of pumping from the aquifer has increased steadily over the years. Natural recharge for the most part has exceeded pumpage and spring flow, two of the major sources of discharge. However, due to increased water demand for growing urban areas and for irrigation, the water needs of the region now exceed the historical availability of water. For example, during a long drought from 1947 to 1956, two of the largest springs experienced serious reduction in discharge. Comal Springs ceased to flow for 4 months in 1956, and the discharge from San Marcos Springs dropped to a level that threatened important ecosystems dependent upon water in the springs.[6] Since the drought, several species have been listed under the Endangered Species Act of 1973. The San Marcos salamander of San Marcos Springs, the fountain darter fish, and Texas wild rice have all been categorized as endangered. As a result of concern for these endangered species, a 1991 lawsuit was initiated by the Sierra Club against the U.S. Fish and Wildlife Service and other agencies to ensure adequate flow of the springs in order to maintain the ecosystems. The litigation established minimum streamflows required for preservation of the spring environment. Unfortunately, historical data clearly demonstrate that spring flows cannot be maintained during serious droughts, so the conflict will continue. In addition, increasing population growth has intensified water demands, and there are no potential alternative water resources that can provide abundant, high-quality, inexpensive water when compared with the Edwards aquifer. Potential resolutions to the water conflicts of the Edwards aquifer are likely to be expensive, not readily available, and certainly not agreeable to all parties.

Further complicating matters, downstream from the recharge zone, surface-water resources remain important to cities such as Corpus Christi. However, flows are required to maintain the ecological integrity and health of Gulf Coast estuaries in Texas. This flow is absolutely necessary to maintain habitat in a healthy estuarine ecosystem.[7]

Water shortages are not the only problems threatening the aquifer. For example, in the Austin area, studies of Barton Springs suggest that both groundwater and surface waters in some places contain a higher-than-normal concentration of several pollutants, including sediment, hydrocarbons, pesticides, nitrates, heavy metals, and bacteria. Examination of the distribution and levels of these pollutants relative to local land use suggest that there is a correspondence between contamination and those parts of the aquifer where urban growth and development have been the greatest.[7]

Potential solutions to future water shortages in the Edwards aquifer region include increasing water supplies, decreasing water demands, and managing existing water resources more efficiently through measures such as water conservation. The last solution seems to be the most likely approach. Presently, over one-half of the water use of the aquifer is for urban supply, and agricultural and rural supply uses the rest.[7] This use distribution is atypical; agricultural water demands generally far exceed urban demands. Water conservation efforts, including water reuse and augmentation of spring flow during droughts, could help alleviate water shortages in the Edwards aquifer region.

The Edwards aquifer is an important case history for water resources management. At the center of the case is an important natural water resource in which geologic, hydrologic, biological, political, legal, social, and economic factors are all playing a role.

Clearly, the aquifer will continue to be a source of conflict as the various interests sort out the future of the precious water resources in this part of Texas. Water managers have predicted that by the year 2050, the total water demand in the region may increase by about 50 percent. However, water withdrawals necessary to maintain the ecosystem and health of the environment are thought to be about 10 percent less than is currently being withdrawn. Of course, there are natural ebbs and flows as a result of variable streamflow; discharge from wells may be greater in some years than others. However, during droughts, all users of the water will be stressed. Therefore, groundwater management plans for the Edwards aquifer, including how to quantify water needs for ecosystems, are being developed with the assumption that deficits in the water supply will steadily grow over time.

while two-thirds of the water use occurs south of San Francisco (mostly in the Los Angeles region), where there is a deficit. In recent years, canals constructed by both the California Water Project and the Central Valley Project have moved tremendous amounts of water from the northern to the southern part of the state (**Figure 13.20**). The diversion of waters has adversely affected ecosystems, especially fisheries in some northern California rivers.

Los Angeles is not unique; many other large cities in the world must seek water from areas increasingly farther away. For example, New York City has imported water from nearby areas for more than 100 years. Water use and supply in New York City represent a repeating pattern. Originally, local groundwater, streams, and the Hudson River were used. However, water needs exceeded local supply; in 1842, the first large dam was built more than 48 km (30 mi) north of the city. As the city expanded rapidly from Manhattan to Long Island, water needs again increased. The sandy aquifers of Long Island were at first a source of drinking water, but this water was removed faster than rainfall replenished it. Local cesspools contaminated the groundwater, and salty ocean water intruded (see the chapter-opening case history). A larger dam was built at Croton in 1900, but further expansion of the population brought repetition of the same pattern: initial

(a)

(b)

FIGURE 13.20 Moving water to people (a) California aqueducts. (b) California aqueduct in the San Joaquin Valley. *(Richard R. Hansen/Photo Researchers, Inc.)*

use of groundwater, pollution and exhaustion of the resource, followed by building new, larger dams in forested areas farther upstate. The trend of cities to import water continues. For example, San Diego, California, is bargaining with agricultural water districts to the east in the Coachella Valley to purchase water. Additional water sources are needed to fuel the city's development and establish a water supply independent of Los Angeles, its large neighbor to the north, from which it currently receives water. Development in urban centers lacking an adequate local water supply now or in the future is becoming a problem for many cities, including Atlanta, New York, Miami, Chicago, Austin, Denver, Los Angeles, and San Diego. Perhaps development and populations of people in such areas should be limited, and more people should move closer to the water supply. This solution may be preferable from an environmental perspective because less water would need to be transported long distances. More water could be used locally near its site of origin. Developing areas near water sources would allow more flexibility in water use, and less water would be lost through evaporation and seepage from aqueducts, leaving more water for ecosystems.

Trends in Water Use

Water use on a global basis is about 70 percent for agriculture, 20 percent for industry, and 10 percent for urban and rural homes. Trends in water withdrawals in the United States (**Table 13.3**) provide insight that is both interesting and necessary for managing our water resources. **Figure 13.21a** (page 451) shows trends in freshwater withdrawals from 1950 through 2005 (the most recent government data). These data suggest:

- Surface-water withdrawals far exceed groundwater withdrawals.
- Water withdrawals increased until 1980 and have since decreased and leveled off. The population of the United States was about 151 million in 1950 and continued to increase, reaching 301 million in 2005. Thus, during the period when water withdrawals decreased and leveled off (1980–2005), population was increasing. This trend suggests better water management and conservation during the 25-year period.[8]

Figure 13.21b shows trends in freshwater and saline water withdrawals by water-use category from 1960 through 2005. These data show that:

- Irrigation needs and the thermoelectric industry are the primary consumers of water.
- Use of water by the public in both urban and rural sectors has increased through the period, a trend presumably related to the increase in population of the country.
- The use of water by agriculture for irrigation leveled off in 1980 and has slightly decreased since then. This change presumably is related to efforts in water conservation.
- Water used for thermoelectric power increased dramatically from 1960 to 1980, as numerous power plants began operating; usage has since decreased because of more efficient use of water.
- Since 1980, industry has used significantly less freshwater. This decrease is due, in part, to new technologies that require less water, as well as to improved plant efficiencies and increased water recycling.

There are encouraging indications that the public is generally more aware of our water resources and the need to conserve them. As a result, water demands have been reduced in many states. Another encouraging sign is that use of reclaimed wastewater is now much more common, about 1 billion gallons per day, which is about five times what it was 50 years ago.[8] More significantly, the trend is continuing as more innovative ways are found to reuse water, particularly reclaimed wastewater. Data for Figures 13.21a and b are shown in Table 13.3. Notice that, while water use for irrigation has decreased by 8 percent since 2000, water for thermoelectric power (although leveling off and decreasing slightly since about 1980) still increased 3 percent. Since 1950, water for thermoelectric power has increased by 5 times, while that for irrigation has increased much less, at about 50 percent. This demonstrates the tremendous increase in use of thermoelectric power in the past 60 years.

Water Conservation

What can be done to use water more efficiently and reduce withdrawal and consumption? Irrigation is one of the largest consumptive uses, and improved

TABLE 13.3 **Trends in Estimated Water Use in the United States from 1950–2005 (in Billions of Gallons Per Day)**

	Year												Percent change 2000–2005
	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	
Population, in millions	150.7	164.0	179.3	193.8	205.9	216.4	229.6	242.4	252.3	267.1	285.3	300.7	+5
Total withdrawals	180	240	270	310	370	420	430	397	404	399	413	410	−1
Public supply	14	17	21	24	27	29	33	36.4	38.8	40.2	43.2	44.2	+2
Rural domestic and livestock													
Self-supplied domestic	2.1	2.1	2.0	2.3	2.6	2.8	3.4	3.32	3.39	3.39	3.58	3.83	+7
Livestock	1.5	1.5	1.6	1.7	1.9	2.1	2.2	2.23	2.25	2.28	2.38	2.14	−10
Irrigation	89	110	110	120	130	140	150	135	134	130	139	128	−8
Thermoelectric power	40	72	100	130	170	200	210	187	194	190	195	201	+3
Other													
Self-supplied industrial	37	39	38	46	47	45	45	25.9	22.6	22.4	19.7	18.2	−8
Mining	—	—	—	—	—	—	—	3.44	4.93	3.72	4.50	4.02	−11
Commercial	—	—	—	—	—	—	—	1.23	2.39	2.89	—	—	—
Aquaculture	—	—	—	—	—	—	—	2.24	2.25	3.22	5.77	8.78	+52
Source of water													
Ground													
Fresh	34	47	50	60	68	82	83	73.4	79.6	76.4	84.3	79.6	−5
Saline	—	0.6	0.4	0.5	1.0	1.0	0.93	0.66	1.22	1.11	2.67	3.02	+13
Surface													
Fresh	140	180	190	210	250	260	280	263	255	261	265	270	+2
Saline	10	18	31	43	53	69	71	59.6	68.2	59.7	61.0	58.0	−5

Source: Kenny, J. F., et al. 2010 Estimated use of water in the United States in 2005. U.S. Geological Survey Circular 1344.

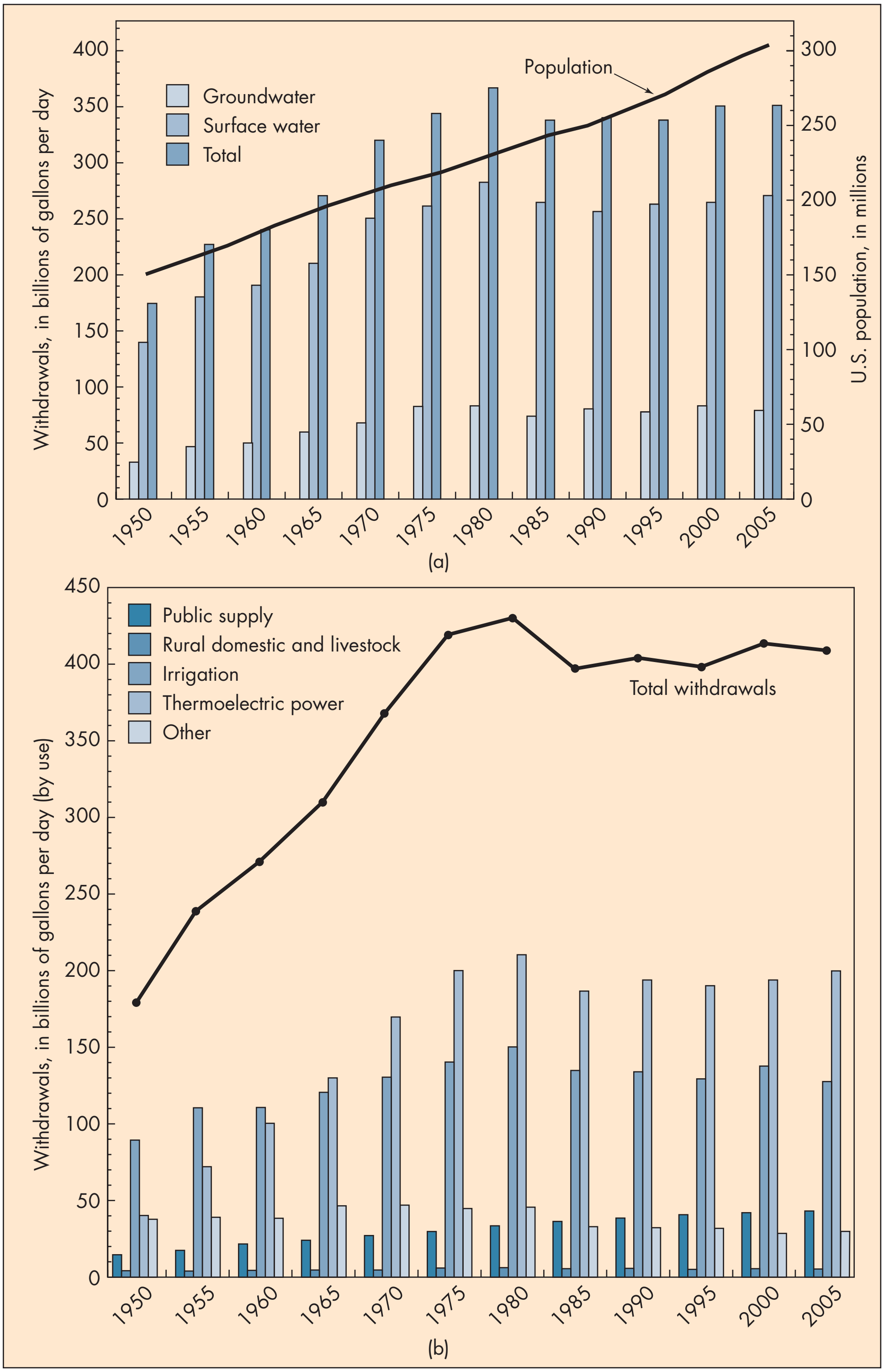


FIGURE 13.21 Trends in U.S. water withdrawals (a) Freshwater withdrawals by water-source category (1950–2005) and (b) total (fresh and saline) withdrawals by water-use category (1960–2005). *(Kenny, J. F., et al. 2010. Estimated Use of Water in the United States in 2005. U.S. Geological Survey Circular 1344)*

agricultural irrigation could reduce water withdrawals by between 20 percent and 30 percent. Poor irrigation practices waste a tremendous amount of water. In some cases, only a small percentage of the irrigation water used actually goes to the target plant. Techniques to improve water conservation for agricultural irrigation include using lined and covered canals that reduce seepage and evaporation; computer monitoring and scheduling of water releases from canals; a more integrated use of

surface waters and groundwaters; night irrigation, which reduces the amount of evaporation; improved irrigation systems, such as sprinklers and drip irrigation; and better land preparation for water application.

Domestic use of water (urban and rural) accounts for only 10 percent of the total national withdrawals. However, domestic use is concentrated, and it poses major local problems. Withdrawal of water for domestic use may be substantially reduced at a relatively small cost with more efficient bathroom and sink fixtures, nighttime watering of lawns and gardens, and drip irrigation systems for domestic plants.

Water removal for thermoelectricity could be reduced as much as 25 to 30 percent by using cooling towers designed to use less or no water. Manufacturing and industry could curb water withdrawals by increasing in-plant treatment and recycling of water or by developing new equipment and processes that require less water. The field of water conservation is changing so rapidly that it is expected that a number of innovations will reduce the total withdrawals of water despite increased consumption.[4]

Virtual Water: Conservation of Water at the Global Scale

Water resources of an area or a region are usually stated in terms of a drainage basin or groundwater reservoir that can produce a volume of water over a specific time, such as cubic meters or acre-feet of water per year. We can also discuss water resources on a global scale, in terms of what is known as **virtual water**, defined as the amount of water necessary to produce a product, such as a home appliance or a crop such as wheat.[9–11] The virtual water content is measured at the place where the product is produced or the crop grown, and it is known as "virtual" because the water content in the product or crop is very small relative to the amount of water used to produce the commodity.[9]

The amount of virtual water to produce crops and animals is surprisingly large and variable. For example, how much water is required to produce a cup of coffee? The answer to the question is simple: Coffee is an important crop for many countries and the major social drink in much of the world. Many a romance has started with the question: Would you like a cup of coffee? Answering the question as to the volume of water used to produce a cup of coffee requires knowing how much water is required to produce the coffee berries (that contain the bean) and the roasted coffee. The question is complicated by the fact that water use to raise coffee varies from location to location, as does the yield of coffee berries. Much of the water in coffee-growing areas is free, in that it comes from rain. However, that does not mean it does not have value. It takes about 140 L (40 gal) to produce one cup of coffee. The amount of water to produce a ton of a particular crop is variable, from a low of about 175 m^3 for sugarcane to 1,300 m^3 for wheat, 3,400 m^3 for white rice, and 21,000 m^3 for roasted coffee. For the meat we eat, the amount per ton is 3,900 m^3 for chicken, 4,800 m^3 for pork, and 15,500 m^3 for beef.[9]

The concept of virtual water demonstrates that people consuming crops in Europe or China directly influence and impact the water resources of the United States through the products they import. The United States produces food products that are exported around the world with consequences to U.S. regional water supply and environmental concerns, including depletion of groundwater resources.

The concept of virtual water is useful in water resource planning. A country with an arid climate with restricted water resources can choose between development of those resources for agriculture or other water uses, such as to support wetland ecosystems or a growing human population. For example, the average global amount of water necessary to produce a ton of white rice is about 3,400 m^3 (nearly 900,000 gal). Growing rice in countries with abundant water resources makes sense. For countries with an arid environment, it might be wise to import rice and save their water resources for other purposes. For example, Jordan imports about 7 billion m^3 of virtual water per year by importing those food items requiring a lot of water to produce. As a result, Jordan withdraws only about 1 billion m^3 of water per year from its limited domestic water resources. Egypt, on the other hand, has the Nile River and is much less dependent on imported virtual water than is Jordan.[9]

Water conservation at the global level is important in sustaining our total global water supply. At present, the international trade markets in virtual water reduce total global agricultural water use by

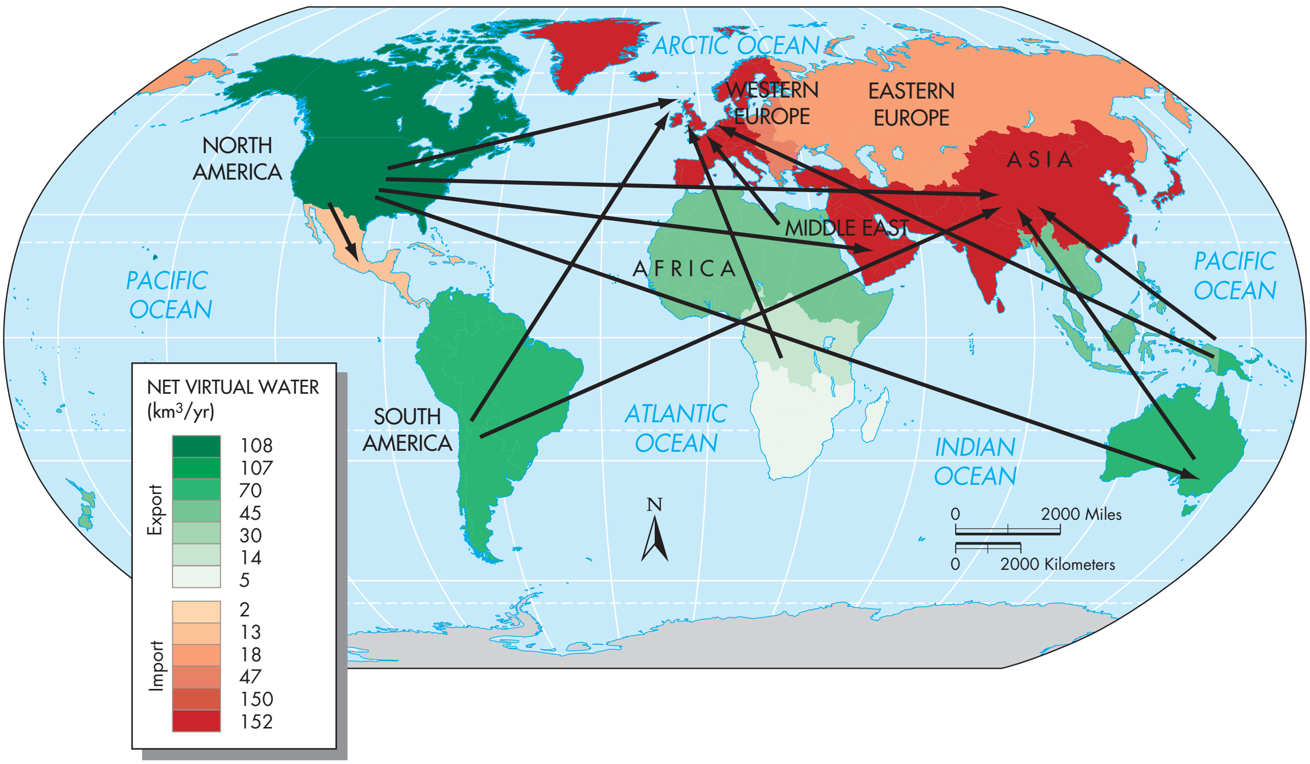


FIGURE 13.22 Virtual water balances and transfers Notice much of the virtual water exports are from North America (U.S. and Canada). 1 Gm^3 is one billion cubic meters. *(Hoekstra, A. Y., ed. 2003. Virtual water trade.* Proceedings of the International Expert Meeting on Virtual Water Trade. *Value of Water Research Report Series 12. Delft, the Netherlands: IHE)*

about 5 percent.[9] **Figure 13.22** shows net virtual water budgets (balances) for major trades. The balance is determined by import minus export in cubic kilometers of virtual water, where 1 km^3 is 10^9 m^3 (i.e., 1 billion m^3). For example, when Canada (which has abundant water resources) exports wheat and other food products to countries where water resources are not as abundant, virtual water is exported. As a result, countries that import food products that demand a lot of water to grow them locally have more water available for domestic drinking supply, water to produce manufactured goods they require, and water to support ecosystems.

Using the concept of virtual water has several advantages:[11]

- Promoting efficient use of water from a local scale to a global scale. Trading of virtual water can conserve global water resources by producing products that require a lot of water in places where water is abundant and can be efficiently used. When those products are exported to places where water is scarce or difficult to use efficiently, water is conserved, and real water savings are realized.
- Assisting countries and regions to obtain water security. Virtual water can be thought of as an alternative, additional water supply that helps solve geopolitical problems between nations.
- Knowing the virtual water content of the products we produce and where and how they are produced creates an increased awareness of what the water demand is and how water savings might be realized.

13.7 Water Management in the Future

Managing water resources is a complex issue that will become more difficult as the demand for water increases (see A Closer Look: Management of the Colorado River). Although water supply problems are most serious in the southwestern United States and other arid and semiarid parts of the world, large cities in more humid regions, such as New York and

A Closer Look

Management of the Colorado River

The Colorado River is the primary river in the southwestern United States, and its water is an important resource. Managing the Colorado River has two aspects: (1) managing the water resources for people and (2) managing the river in the Grand Canyon to maintain the river environment. We will discuss each of these in turn.

Managing the Water

No discussion of water resources and water management would be complete without a mention of the Colorado River basin and the controversy that surrounds the use of its water. People have been using the water of the Colorado River for about 800 years. Early Native Americans in the basin had a highly civilized culture with a sophisticated water-distribution system. Many of their early canals were later cleared of debris and used by settlers in the 1860s.[13] Given this early history, it is somewhat surprising to learn that the Colorado was not completely explored until 1869, when John Wesley Powell, who later became director of the U.S. Geological Survey, navigated wooden boats through the Grand Canyon.

Although the waters of the Colorado River basin are distributed by canals and aqueducts to many millions of urban residents and to agricultural areas, such as the Imperial Valley in California, the basin itself, with an area of approximately 632,000 km^2 (244,017 mi^2), is only sparsely populated. Yuma, Arizona, with approximately 42,000 people, is the largest city on the river, and within the basin only the cities of Las Vegas, Phoenix, and Tucson have more than 50,000 inhabitants. Nevertheless, only about 20 percent of the total population of the basin is rural. Vast areas of the basin have extremely low densities of people, and in some areas measuring several thousand square kilometers there are no permanent residents.[13,14] The headwaters of the Colorado River are in the Wind River Mountains of Wyoming, and in its 2,300 km (1,430 mi) journey to the sea, the river flows through or abuts seven states—Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona, and California—and Mexico (**Figure 13.C**). Although the drainage basin is very large, encompassing much of the southwestern United States, the annual flow is only about 3 percent of that of the Mississippi River and less than one-tenth that of the Columbia. Therefore, for its size, the Colorado River has only a modest flow; however, it has become one of the most regulated, controversial, and disputed bodies of water in the world. Conflicts that have gone on for decades extend far beyond the Colorado River basin, involving large urban centers and

FIGURE 13.C The Colorado River basin This diagram shows major reservoirs and the division of the watershed for management purposes. The delta, once a large wetland area at the head of the Gulf of Mexico, has been severely degraded as a result of diversion of water for various uses.

developing agricultural areas of California, Colorado, New Mexico, and Arizona. The need for water in these semiarid areas has resulted in overuse of limited supplies and deterioration of water quality. Interstate agreements, court settlements, and international pacts have periodically eased or intensified tensions among people who use the waters along the river. The legacy of laws and court decisions, along with changing water-use patterns, continues to influence the lives and livelihood of millions of people in both Mexico and the United States.[15]

The waters of the Colorado River have been appropriated among the various users, including the seven states and the Republic of Mexico. This appropriation has occurred through many years of negotiation, international treaty, interstate agreements, contracts, federal legislation, and court decisions. As a whole, this body of regulation is known as the Law of the River. Two of the more important early documents in this law were the Colorado River Compact of 1922, which divided water rights in terms of an upper and a lower basin, and the treaty with Mexico in 1944, which promised an annual delivery of 1.85 km^3 (1.5 million acre-feet [1 acre-foot is the volume of water covering 1 acre to a depth of 1 ft], or 325,829 gal) of Colorado River water to Mexico. More recent was a 1963 U.S. Supreme Court decision involving Arizona and California. Arizona refused to sign the 1922 compact and had a long conflict with California concerning the appropriation of water. The court decided that southern California must relinquish approximately 0.74 km^3 (600,000 acre-feet) of Colorado River water. Finally, in 1974, the Colorado River Basin Salinity Control Act was approved by Congress. The act authorized procedures to control adverse salinity of the Colorado River water, including construction of desalinization plants to improve water quality.

Issues of water management in the Colorado River remain complex because all the water is spoken for as demand for more water increases. The history of water management in the Colorado illustrates major questions likely to be faced in other parts of the Southwest in coming years: How can we appropriate limited water resources? and How can we maintain water quality?

As an example of a complex water management issue, consider the All American Canal. The canal is located along the U.S. side of the border with Mexico (see Figure 13.20a). The canal is lined with earth, and, as a result, water from the Colorado River that flows through the canal seeps into the ground. That water is a source of argument and is developing into a political water war. A 36 km (23 mi) section of the canal that delivers water to San Diego may be lined with concrete. The objective is to stop the loss of water that seeps into the ground from the canal. However, this will adversely affect Mexican farmers. Billions of gallons of water seep into the ground and replenish groundwater resources that Mexican farmers have used to irrigate their fields for over 60 years. The treaty of 1944 with Mexico doesn't prohibit lining the canal, but Mexicans argue that it is unethical to take water they have used for decades. The Mexican farmers say that if they lose the water, farms will fail, leading to increased illegal immigration into the United States. Anything that reduces the opportunities in Mexico may lead to increased immigration, but the ethical argument is stronger. Water used for decades in Mexico, even though the water was not anticipated when the canal was constructed, sets a precedent we need to honor.

Managing the Colorado River in the Grand Canyon

The Grand Canyon of the Colorado River (**Figure 13.D**) provides a good example of a river's adjustment to the impact of a large dam. In 1963, the Glen Canyon Dam was built upstream from the Grand Canyon (Figure 13.C). Construction of the dam drastically altered the pattern of flow and channel process downstream; from a hydrologic viewpoint, the Colorado River had been tamed. Before the Glen Canyon Dam was built, the river reached a maximum flow in May or June during the spring snowmelt; then flow receded during the remainder of the year, except for occasional flash floods caused by upstream rainstorms. During periods of high discharge, the river had a tremendous capacity to transport sediment (mostly sand and silt) and vigorously scoured the channel. The high floods also moved large boulders off the rapids, which formed because of shallowing of the river where it flows over alluvial fan or debris flow deposits delivered from tributary canyons to the main channel. As the summer low flow approached, the stream was able to carry less sediment, so deposition along the channel formed large bars and terraces, known as *beaches* to people who rafted the river.

After the dam was built, the mean annual flood (the average of the highest flow each year) was reduced by about 66 percent, and the 10 year flood was reduced by about 75 percent. On the other hand, the dam did control the flow of water to such an extent that the median discharge actually increased about 66 percent. The flow is highly unstable, however, because of fluctuating needs to generate power, and the level of the river may vary by as much as 5 m (16 ft) per day. The dam and reservoir trap sediment from moving downstream, greatly reducing sediment load of

FIGURE 13.D The Colorado River in the Grand Canyon The sandbar "beach" is being used by river rafters whose numbers have increased and affect the canyon. The number of people allowed to raft through the canyon is now restricted. *(Craig Lovell/Eagle Visions Photography/Alamy)*

the river immediately downstream from the dam. As a result, some of the large sandbars, which are valuable habitat, are starved of sand and are eroding. A lesser reduction in sediment load occurred farther downstream because tributary channels continued to add sediment to the channel.[16]

The change in hydrology of the Colorado River in the Grand Canyon has greatly changed the river's morphology. The rapids may be becoming more dangerous because large floods that had previously moved some of the large boulders farther downstream no longer occur.

Changes in the river flow, mainly deleting the high flows, have also resulted in vegetational shifts. Before the dam was built, three nearly parallel belts of vegetation were present on the slopes above the river. Adjacent to the river and on sandbars grew ephemeral plants, which were scoured out by yearly spring floods. Above the high-water line were clumps of thorned trees (e.g., mesquite, catclaw acacia) mixed with cactus and Apache plume. Higher yet was a belt of widely spaced brittle brush and barrel cactus.[17] Closing the dam in 1963 tamed the spring floods for 20 years, and plants not formerly found in the canyon, including tamarisk (i.e., salt cedar) and indigenous willow, became established in a new belt along the riverbanks.

In June 1983, a record snowmelt in the Rocky Mountains forced the release of about three times the amount of water normally released and about the same amount as an average spring flood before the dam. The resulting flood scoured the riverbed and riverbanks, releasing stored sediment that replenished the sediment on sandbars and scoured out or broke off some of the tamarisk and willow stands. The effect of the large release of water was beneficial to the river environment and emphasizes the importance of the larger floods in maintaining the system in a more natural state. Later, as an experiment, between March 26 and April 2, 1996, a "test flood" was released from the dam in order to redistribute the sand supply. The floods resulted in the formation of 55 new beaches and added sand to 75 percent of the existing beaches. It also helped rejuvenate marshes and backwaters, which are important habitats to native fish and some endangered species. Water released from the dam is cold, and a trophy trout fishery has been established. Native fish that prefer warmer water, including large (up to 6 ft long) squaw fish, are threatened with extinction due to habitat transformation and introduction of the trout. The experimental flood was hailed a success,[18] although a significant part of the new sand deposits was subsequently eroded away.[19]

The 1996 test flood remobilized sand, scouring it from the channel bottom and banks of the Colorado River below Glen Canyon Dam and depositing it on sandbars. However,

little new sand was added to the river system from tributaries to the Colorado River because they were not in flood flow during the test flood. The sand was mined from the river below the dam; as such, it is a limited, nonrenewable source that cannot supply sand to sandbars on a sustainable basis. A new, creative idea has recently been suggested.[19] The plan is to use the sand delivered to the Grand Canyon by the Little Colorado River, a relatively large river with a drainage area of 67,340 km^2 (26,000 mi^2) (Figure 13.C), which joins the Colorado River in the canyon downstream from Lee's Ferry. In 1993, a flood on the Little Colorado River delivered a large volume of sand to the Colorado River in the Grand Canyon, and prominent beaches were produced. Unfortunately, a year later, the beaches had been almost entirely eroded away by the flow of the Colorado River. The problem was that the beaches were not deposited high enough above the bed of the Colorado and so were vulnerable to erosion from normal postdam flows. The idea suggested in the new study is to time the releases of flood flows from Glen Canyon Dam with sand-rich spring floods of the Little Colorado River. The resulting combined flood of the two rivers would be larger, and the new sand from the Little Colorado (**Figure 13.E**) would be deposited higher above the channel bed and would be less likely to be removed by lower flows of the Colorado. Evaluation of the hydrology of the Little Colorado River suggests that the opportunity to replenish sand on the beaches occurs, on average, once in 8 years. The proposed plan would help restore or re-create river flow and sediment transport conditions that formed and maintained the natural ecosystems of the canyon to be more as they were before the construction of Glen Canyon Dam.[19]

Another impact of the Glen Canyon Dam is the increase in the number of people rafting through the Grand Canyon. Although rafting is now limited to 15,000 people annually, the long-range impact on canyon resources is bound to be appreciable. Before 1950, fewer than 100 explorers and river runners had made the trip through the canyon.

We must concede that the Colorado River of the 1970s and 1980s is a changed river. Despite the 1983 and 1996 floods that pushed back some of the changes, river restoration efforts cannot be expected to return it to what it was before construction of the dam.[16,17,19] On the other hand, better management of the flows and sediment transport will improve and better maintain river ecosystems.

Finally, as a result of upstream water use, the delta of the Colorado River, once a major wetland, has been degraded. Some years, no flow reaches the sea.

FIGURE 13.E The Little Colorado River The Little Colorado River channel has abundant sand to help maintain sandbar "beaches" in the Colorado River. *(Edward A. Keller)*

Atlanta, also face problems. However, there are options available, including locating alternative supplies, better protecting and managing existing supplies, and controlling population growth.

Cities in need of water are beginning to treat water as a commodity, similar to oil or gas, that can be bought and sold on the open market. If cities are willing to pay for water and are allowed to avoid current water regulation, then allocation and pricing, as they are now known, will change. If the cost rises enough, "new water" from a variety of sources may become available. For example, irrigation districts in agricultural areas may contract with cities to supply water to urban areas. This arrangement could be done without negatively affecting crops by using conservation measures to minimize present

water loss through evaporation and seepage from unlined canals. Currently, most irrigation districts do not have the capital to finance expensive conservation methods, but cities in need of water could finance such projects. Clearly, water will become much more expensive in the future, and, if the price is right, many innovative programs are possible.

Luna Leopold, a leader in the study of rivers and water resources, has suggested a new philosophy of **water management**. This new philosophy is based on geologic, geographic, and climatic factors, as well as on the traditional economic, social, and political factors. The management of water resources cannot be successful as long as it is naively perceived primarily from an economic and political standpoint. The term *water use* is more appropriate because we seldom really manage water.[12] The essence of Leopold's water management philosophy is that surface water and groundwater are both subject to natural flux. In wet years, surface water is plentiful, and the near-surface groundwater resources are replenished. During these years, we hope that our flood-control structures, bridges, and storm drains will withstand the excess water. These structures are designed to withstand a particular flow; exceeding that flow may cause damage or flooding. Leopold concludes that we are much better prepared to handle floods than water deficiencies. Specific strategies to minimize hardships must be in place to combat water deficiencies during the dry years. For example, subsurface waters in various locations in the western United States are either too deep to be economically extracted or have marginal water quality. Furthermore, these waters may be isolated from the present hydrologic cycle and, therefore, may not be subject to natural recharge. However, water from these sources could be available if plans were in place for drilling wells and connecting them to existing water lines. Treatment of wastewater for reuse could also be an option in an emergency. Reuse of water on a regular basis might be too expensive or objectionable for other reasons, but advance planning to reuse more treated water during emergencies might be wise.[12]

In wet years, groundwater is naturally replenished. Surface water should be used when it is available, and groundwater should be reserved for dry years. In other words, groundwater could be pumped out at a rate exceeding the replenishment rate in dry years and would be replenished by natural discharge and artificial recharge during wet years. This water management plan recognizes that excesses and deficiencies in water are natural and can be planned for.

13.8 Water and Ecosystems

The major ecosystems of the world have evolved in response to physical conditions that include climate, nutrient input, soils, and hydrology. Changes in these factors affect ecosystems; in particular, human-induced changes may have far-reaching effects. Throughout the world, with few exceptions, people are degrading natural ecosystems. Hydrologic conditions, particularly surface-water processes and quality, are becoming factors that limit the continued existence of some ecosystems, particularly wetlands [20] (see A Closer Look: Wetlands).

Water resources development, such as construction of dams, reservoirs, canals, or aqueducts, have a variety of environmental impacts at a variety of scales. Dams and accompanying reservoirs are often designed to be multifunctional, providing water for agriculture, a mechanism for flood control, and sites for recreational activities. Reconciling these various uses at a given reservoir site is often difficult. For example, water demands for agriculture are generally high during the summer, resulting in lowering of the water level in the reservoir and production of extensive mudflats. People interested in recreation find the low water level and mudflats to be aesthetically displeasing; moreover, the effects of the high water demand and drawdown of the reservoir water may interfere with wildlife by damaging or limiting a fish's spawning opportunities. (See the discussion of dams and reservoirs with water power in Chapter 16.) Dams and reservoirs also tend to instill a false sense of security in persons living downstream of the facilities, who believe they are protected from floods. However, four major environmental effects of dams are:

- Land, with its cultural and biological resources, is lost in the area flooded by the reservoir.
- Ecosystems are fragmented, as migrating fish are blocked from moving upstream of the dam. In the reservoir, hilltop areas with adjacent valleys are transformed to more isolated islands.
- The reservoir traps sediment that is transported from upstream by the rivers and

A Closer Look: Wetlands

The term **wetlands**[21] refers to a variety of landscape features, such as:

- *Swamps:* Wetland that is frequently or continuously inundated by water
- *Marshes:* Wetland that is frequently or continuously inundated by water
- *Bogs:* Wetland that accumulates peat deposits
- *Prairie potholes:* Small marshlike ponds
- *Vernal pools:* Shallow depressions that occasionally (often seasonally) hold water

Some of these features are shown in Figure 13.F. The common feature and operational definition of wetlands is that they are either inundated by water or the land is saturated to a depth of a few centimeters for at least a few days most years. Hydrology, or wetness, and the types of vegetation and soil determine the presence or absence of wetlands. Of these three factors, hydrology is often the most difficult to define because some wet-

(a)

(b)

(c)

FIGURE 13.F Several types of wetlands (a) Chesapeake Bay salt marsh. *(Comstock Images)* (b) Freshwater cypress swamp in North Carolina. *(Cameron Davidson/Getty Images)* (c) Prairie potholes in the Dakotas. *(Macduff Everton/Corbis)*

lands are wet for only a very short period each year. However, the presence of water, even for short periods on a regular basis, does give rise to characteristic wetland soils and specially adapted vegetation. Recognition of wetland soils and vegetation greatly assists in identifying the wetland itself in many cases.[22,23]

Wetlands and their associated ecosystems have many important environmental features:

- Coastal wetlands such as salt marshes provide a buffer for inland areas from coastal erosion and flooding associated with storms or tsunami.
- Wetlands are one of nature's natural filters. Plants in wetlands may effectively trap sediment, nutrients, and pollutants.
- Freshwater wetlands are a natural sponge. During floods, they store water, helping to reduce downstream flooding. The stored water is slowly released after the flood, nourishing low flows of river systems.
- Wetlands are often highly productive lands where many nutrients and chemicals are naturally cycled while providing habitat for a wide variety of plants and animals.
- Freshwater wetlands are often areas of groundwater recharge to aquifers. Some of them, a spring-fed marsh, for example, are points of groundwater discharge.

Although most coastal marshes are now protected in the United States, freshwater wetlands are still threatened in many areas. It is estimated that 1 percent of the nation's total wetlands is lost every 2 years. Freshwater wetlands account for nearly all of this loss. In just the past 200 years, about half of the total wetlands in the United States, including about 90 percent of the freshwater wetlands, have disappeared as a result of being drained for agricultural purposes or urban development.

The damage and degradation of wetlands have led to a growing effort to restore them. Unfortunately, restoration is not usually an easy task, since wetlands are a result of complex hydrologic conditions that may be difficult to restore if the water has been depleted or is being used for other purposes. Researchers are carefully documenting the hydrology of wetlands as well as the movement of sediment and nutrients. As more information is gathered concerning how wetlands work, restoration is likely to be more successful.

streams that enter the reservoir. The trapped sediment reduces the water-storage capacity of the reservoir. More significantly, the reservoir holds sediment that would normally be transported downstream, nourishing the river and coastal environment. When rivers and coasts are deprived of sediment, river erosion occurs downstream of dams, and coastal erosion occurs on beaches.

- The downstream hydrology and sediment transport system change the entire river environment, affecting the organisms that live there (see A Closer Look: Management of the Colorado River).

13.9 Emerging Global Water Shortages

Only recently have we realized that isolated shortages of water are an indication of a global pattern of a resource being depleted.[24] Around Earth, groundwater is being depleted, mined from aquifers mostly used for agriculture; large lakes are drying up, such as the Aral Sea mentioned in Chapter 1; and some large rivers, including the Colorado in the United States and the Yellow in China, run dry in some years and don't reach the sea, while others, such as the Nile in Africa, have seen their discharge to the sea reduced by over 90 percent. Water demand in the past 50 years has tripled as grain (wheat) production to feed people has tripled. During the same 50 years, human population more than doubled. In the next 50 years, human population is expected to increase another 2 to 3 billion, and there is concern that, without very careful management of water resources, there won't be enough water to grow the food for the expected 8 to 9 billion people in 2050. Thus, we see that the emerging water shortage is linked to a potential food shortage. The problem is that the tremendous increase in grain production has been dependent on irrigation water, mostly from groundwater resources. These same resources are being

depleted nearly everywhere grain is grown—for example, the United States, China, India, Pakistan, and Mexico.[24] As water shortages occur, food shortages will follow. The solution is clear: Control human population growth and conserve water. This chapter has outlined a number of ways to conserve our water resources through using less and reclaiming more. To avoid a food crisis, more needs to be done. The good news is that a solution is possible, but it will take a lot of proactive work.

Making The Connection

Linking the Opening Case History About Long Island to the Fundamental Concepts

Consider and discuss the following questions:

1. What are the impacts of population increase and tourism in Long Island on water supply and quality?
2. Is sustainable water management possible on Long island? If you think it is, what should be done? If you think it is not sustainable, what needs to be done?
3. How do science and values link to future planning to manage water resources on Long Island?

Summary

The global water cycle involves the movement, storage, and transfer of water from one part of the cycle to another. The movement of water on land—that is, surface runoff and subsurface flow—is the part of the cycle of most direct concern to people.

Drainage basins, or watersheds, are a basic unit of the landscape. Surface-water runoff varies greatly from one drainage basin to another and is influenced by geographic, climatic, and biological factors.

The major source of groundwater is precipitation that infiltrates the recharge zone on the land surface and moves down through the vadose zone, which is seldom saturated, to the zone of saturation. An aquifer is a zone of Earth material capable of supplying water at a useful rate from a well. Interactions and linkages between surface water and groundwater are important environmentally because pollution in surface water may eventually contaminate the groundwater. Karst areas are particularly vulnerable to pollution.

Water supply is limited, even in areas of high precipitation and runoff, by our inability to store all runoff and by the large annual variation in streamflows. In many areas, groundwater is being mined, resulting in withdrawals that exceed natural replenishment. In some areas, mining of groundwater has permanently changed the character of the land.

Water uses are categorized as offstream, including consumptive, and instream. Multiple instream uses for hydroelectric power, recreation, and fish and wildlife habitat often have conflicting requirements; partitioning water resources to meet the various uses is a controversial subject.

Water conservation is an important objective if Earth's water resources are to be sustained.The concept of virtual water can help promote efficient water use from the local to the global scale.

Water resource management needs a new philosophy that considers geologic, geographic, and climatic factors and utilizes creative alternatives.

Water is an integral part of ecosystems, and its increasing use by people is a major contributor to the degradation of ecosystems. Loss of or damage to wetlands is an area of particular environmental concern in the United States because a significant portion of these ecosystems has already been lost, including 90 percent of the freshwater wetlands.

We are facing a global water shortage linked to food supply. Proactive water management is needed to produce an adequate food supply in the next 50 years as human population grows by 2 to 3 billion new people.

Revisiting Fundamental Concepts

Human Population Growth There is plenty of water on Earth for our present population. However, it is not uncommon to have water shortages because people tend to reside in areas where water resources are limited. Population centers do not coincide with places where the most freshwater is available. As a result, as human population continues to grow, water shortages will become more apparent, particularly in the more arid parts of the world. It is expected that, during the twenty-first century, very serious water shortages will result in some regions, and these are likely to lead to conflicts between nations.

Sustainability One way to avoid water shortages in the future is to ensure that we sustain our present sources. Sustainability means that we will leave to future generations water resources that have not been degraded by human processes. We also wish to ensure that the ecosystems of the world have enough water to remain healthy in the future. Therefore, development of sustainable water management is of prime concern to persons responsible for managing our water resources. Aspects of the sustainable water management program will include more efficient use of present water resources, water conservation, and protection of drainage basins so that they will continue to yield high-quality surface water and groundwater.

Earth as a System Our water resources at the global, regional, and local levels are maintained by complex hydrologic systems that involve interactions between surface water and groundwater, both of which are subject to change over a variety of time scales, from several years to several hundred years or longer. As a result, in order to effectively manage water resources, we must understand various parts of the hydrologic system, including climate, geology, and land use. Human change that causes diversion of water from rivers and streams will likely degrade the ecosystems that the water nourished. As a result, to effectively use our water resources, we must pay close attention to how biological systems interact with the hydrologic system.

Hazardous Earth Processes, Risk Assessment, and Perception There are significant risks and hazards associated with water shortages. For example, much of the food we consume is produced by irrigated lands, and our water resources are generally managed to provide sufficient water over a period of years. Use of water resources affects several natural hazards, the foremost of which is flooding, which is the most universally experienced natural hazard.

Scientific Knowledge and Values The science of the water cycle and how it interacts with biological systems is a mature science. We have painstakingly learned how to utilize water for the benefit of people. However, we also recognize that other living things need water, too. To support ecosystems that require water resources, such as wetlands, we need to examine how we value the world around us. When we build a dam or overuse an aquifer, we change the hydrologic conditions and the life that depends upon water resources. Thus, we face a value judgment as to whether we wish to develop more water resources or to better protect ecosystems that are dependent upon the water, such as the unique organisms in the large springs that discharge from the Edwards aquifer.

Key Terms

aquifer (p. 437)
consumptive use (p. 445)
Darcy's law (p. 440)
desalination (p. 445)
drainage basin (watershed) (p. 433)
instream use (p. 445)
karst topography (p. 443)
offstream use (p. 445)
virtual water (p. 452)
water cycle (p. 432)
water management (p. 458)
wetlands (p. 459)

Review Questions

1. What is a watershed or drainage basin?
2. Define *vadose zone*, *zone of saturation*, and *water table*.
3. What is an aquifer?
4. What major factors control the movement of groundwater?
5. What is Darcy's law?
6. What are some of the important interactions between surface water and groundwater?

7. Distinguish between instream and offstream water uses.
8. What is virtual water and why is it important?
9. Who are the biggest users of freshwater?
10. What are some of the ways we may conserve water?
11. Define Luna Leopold's philosophy concerning water management.
12. Define *wetlands*.
13. List some of the important environmental features associated with wetlands.
14. Why might we be facing a global food shortage based on water use?

Critical Thinking Questions

1. What sort of wetlands are found in your region? Outline a plan to inventory the wetlands and make an assessment of how much of the resource has been lost or damaged. Is wetlands restoration possible in your region, and what would you need to do to make it successful?
2. Evaluate the looming groundwater crisis over the Edwards aquifer in Texas. Consider social, economic, and environmental aspects.
3. Do you think that we are living in a "food bubble" that may burst in the next few decades? That is, will links between food and water lead to a drop in food production with increasing human tragedy?

Companion Website

www.mygeoscienceplace.com

PEARSON mygeoscience place™

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology.*
- **Test** yourself with online quizzes.

Pig farms in North Carolina flooded in 1999 during Hurricane Floyd. *(Courtesy of Richard J. Dove)*

14 Water Pollution

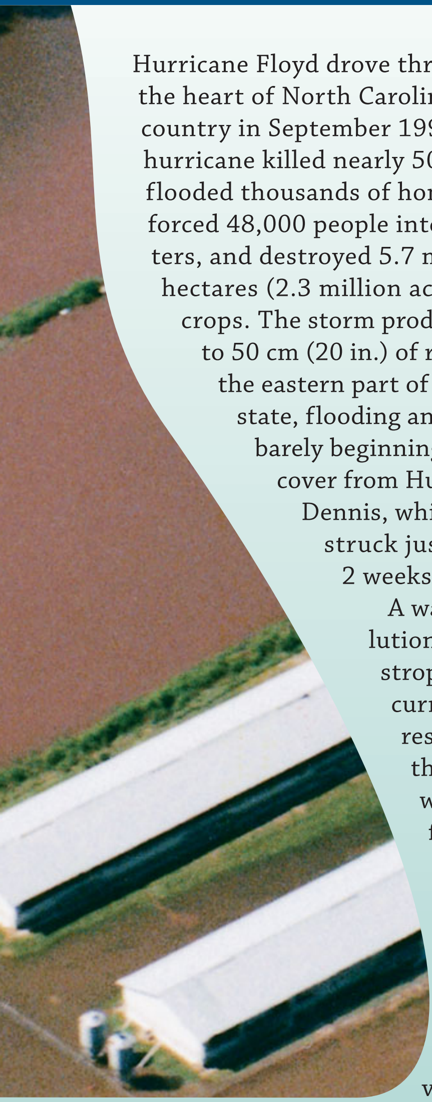
Learning Objectives

In Chapter 13, we learned that the utilization of our water resources often goes hand in hand with the threat of water pollution. For example, we learned that the urban land use of Long Island, New York, has resulted in groundwater pollution. However, by far the most serious water resource problem is the lack of a pollution-free water supply for billions of people in many regions of the world. In this chapter, we will focus on the following learning objectives:

- Know the basic principles of water pollution
- Understand why lack of clean, disease free drinking water is the most serious water quality problem facing the world today
- Be familiar with the common water pollutants
- Understand the methods for treating water pollution
- Understand the important processes related to wastewater treatment and renovation

Case History

North Carolina's Bay of Pigs



Hurricane Floyd drove through the heart of North Carolina's pig country in September 1999. The hurricane killed nearly 50 people, flooded thousands of homes, forced 48,000 people into shelters, and destroyed 5.7 million hectares (2.3 million acres) of crops. The storm produced up to 50 cm (20 in.) of rain in the eastern part of the state, flooding an area barely beginning to recover from Hurricane Dennis, which had struck just 2 weeks earlier.[1]

A water pollution catastrophe occurred as a result of the floodwaters from Hurricane Floyd. However, it was a preventable catastrophe that environmentalists had anticipated. Although North Carolina has a long history of hog production, the population of pigs swelled from about 2 million in 1990 to about 10 million by 2010, making North Carolina the second-largest pig-farming region in the nation (**Figure 14.1**). In the early 1990s, the state allowed large commercial pig farms to expand. Large automated confining farms were built to house hundreds or thousands of pigs. North Carolina did not impose restrictions on their locations, and many of these "factory farms" were constructed on floodplains or reclaimed wetlands. Each pig produces approximately 2 tons of waste a year, so the North Carolina pigs were putting out approximately 20 million tons of waste a year. Waste consisting of manure and urine was flushed out of the farms into 4 m (13 ft) deep, unlined lagoons the size of football fields. The only waste treatment in these lagoons was natural bacterial decay. The farmers argued that, after the waste was degraded in the lagoons, the liquid could be sprayed onto crops as fertilizer. In reality, however, few crops were grown in the area; in addition, heavy rains sometimes caused the ponds to overflow and run into rivers. No precautions were taken for the flood hazard, and, as a result, large parts of eastern North Carolina became cesspools with lagoons. An early warning came in June 1995; the citizens of Onslow County, on North Carolina's coastal plain, were rudely awakened by a very unpleasant sight. A pig-waste holding lagoon had collapsed, sending approximately 95 million L (25 million gal) of concentrated pig feces and urine across a road and over fields into the New River. During the next 24 hours or so, the noxious mass of waste traveled approximately 35 km (22 mi) down the river, slowing up near the city of Jacksonville. Some of the waste found its way into the New River estuary, where its adverse effects on marine life lasted approximately 3 months. Researchers investigating this spill in the New River found numerous carcasses of fish littering the bank and hanging in stream-side brush. The water had turned murky brown and produced a nauseating stench.[2]

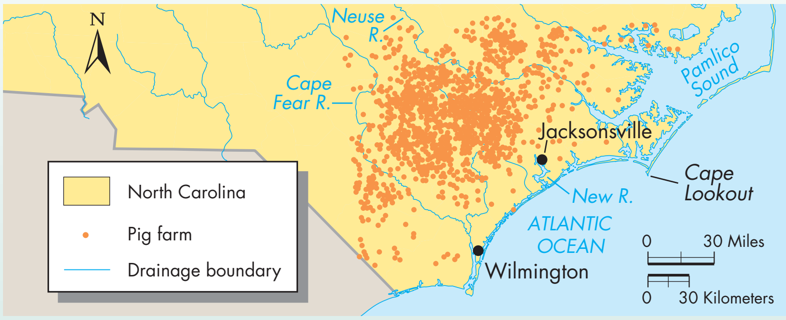


FIGURE 14.1 Several thousand factory-style hog farms Map of part of the pig-farming region in North Carolina. *(Modified after Mallin, M. A. 2000. Impacts of industrial animal production on rivers and estuaries.* American Scientist *88(1):26–27)*

The favorable regulatory climate and availability of inexpensive waste-disposal systems were responsible for the phenomenal growth in the North Carolina pig population in the 1990s. Most of the factory-style animal operations are located in the lower Cape Fear and New River watersheds (Figure 14.1). The concentration of pig farms in this area has transformed the region into a natural laboratory for examining the impact of industrial-scale animal production and its waste products on river and estuarian systems. When Hurricane Floyd struck in 1999, more than 38 pig lagoons washed out, and perhaps as much as 95,000 m^3 (250 million gal) of pig waste was dumped into creeks, rivers, and

wetlands (**Figure 14.2**). After the hurricane, approximately 250 pig operations were flooded out or had overflowing lagoons. Many of the flooded lagoons were upriver from towns that flooded, and the waste moved with the floodwater through schools, churches, homes, and businesses. People along the rivers reported that the stench was overwhelming. The state Department of Agriculture estimated that approximately 30,000 hogs, 2 million chickens, and 735,000 turkeys had died. Most of the poultry carcasses were piled up and left to rot. Mobile incinerators that were moved to the area to burn floating hog carcasses were overwhelmed, leaving the farmers to bury the animals in shallow pits (**Figure 14.3**). The pits were supposed to be dry and at least 1 m (3.3 ft) deep; unfortunately, there was not always time to find dry ground, and, for the most part, the pits were dug and filled with no oversight. Many of the burials took place on floodplains, and it can be expected that, as the pig carcasses rot, bacteria will leak into groundwater and surface waters for some appreciable time.[1]

After the 1995 spills, environmentalists raised warnings concerning the location of the pig farms. They pointed out that hurricanes and flooding were common on North Carolina's coastal plain. However, the pig farm corporations are very rich and politically powerful; they fight long and hard to resist any change in their operations. Incredibly, they asked for approximately $1 billion in grants to repair or replace the agricultural facilities lost in 1995. They also asked for exemption from the Clean Water Act for a period of 6 months so that waste from lagoons might be discharged directly into streams. Fortunately, these requests were not granted.[1]

Even before the catastrophe caused by Hurricane Floyd, the pig farm situation in North Carolina had grown into a scandal reported by newspapers, local television shows, and the national news show *60 Minutes*. Finally, in 1997, a state law was enacted that prohibited building new waste lagoons and sewage plants on floodplains. In the spring of 1999, the governor of North Carolina proposed a 10-year plan to introduce new waste-treatment technology and phase out the state's 4,000 animal waste lagoons. Unfortunately, Hurricane Floyd occurred before these changes could be enacted. Pig farms used the hurricane as a scapegoat, blaming it for the environmental catastrophe. However, it was clearly a human-induced catastrophe. Other states, such as Iowa, have large pig farms but have much more stringent environmental controls. Given North Carolina's frequent hurricanes,

FIGURE 14.2 Ruptured hog waste lagoon This lagoon, in Pitt County, North Carolina, ruptured as a result of Hurricane Floyd. *(USGS/U.S. Department of the Interior)*

FIGURE 14.3 Hogs killed by flooding Floodwaters from Hurricane Floyd inundated many pig farms, and pig carcasses were buried in shallow pits. *(Chris Seward/News and Observer Publishing Co)*

restricting factory farms from floodplains would seem to be a "no brainer." However, this is only the first step in controlling the waste problem posed by the pig farms in North Carolina. In order to prevent a similar catastrophe in the future, pig farmers will have to replace the use of waste lagoons with alternative waste-management practices.[1,2] Several years ago, citizens formed the "Hog Roundtable," a coalition of health, civic, and environmental groups, to control hog farming. Results included a mandate to phase out hog lagoons, expanded requirements for a buffer zone between hog farms and wells supplying water for people, requirements for larger buffers between fields being sprayed with pig waste and surface waters, and halting of construction of a proposed slaughterhouse that would allow even more hog farms to be constructed.

Hurricane Floyd proved that large-scale agriculture is vulnerable to environmental catastrophes. Economic growth and livestock production must be carefully planned to anticipate problems; waste-management facilities must be designed that will not harm the environment. Of course, North Carolina is not the only place where environmental damage from pig production has occurred. Fish kills have occurred in Missouri and Iowa as well. Clearly, these examples demonstrate the need for the design of environmentally safe industrial agricultural practices. To this end, research with the objective to treat waste produced by pig farms has been ongoing since about 1997. The overall objective is to eliminate the discharge of waste to the land surface water and groundwater while also eliminating odors and pathogens. Three related processes are[3]:

1. Recovery of organic matter from pig waste by separating solids from liquid waste
2. Removal of ammonia and phosphorus from the wastewater
3. Disposal of the treated wastewater

An on-site treatment facility (see **Figure 14.4**) at a pig farm in Duplin County, North Carolina, replaced a swine lagoon. The plant successfully removed more than 97 percent of the solids, 99 percent of the ammonia, 95 percent of the phosphorus, and 97 percent of the odor-causing components.[3] Following treatment, the disinfected (cleaned) wastewater was discharged into the old swine lagoon, which changed color from polluted brown water to much cleaner, clear water. As a byproduct, the treatment produced a liquid fertilizer as well as solid calcium phosphate (also a fertilizer) that can be used to nourish feed crops for the pigs or be sold. In North Carolina, waste treatment facilities for pig farms are necessary because, in 2007, the state passed legislation to ban construction or expansion of new lagoons and spray fields. The legislation also encourages pig farms to extract methane from the pig waste (using bacteria in anaerobic digesters) to be used as an energy source.

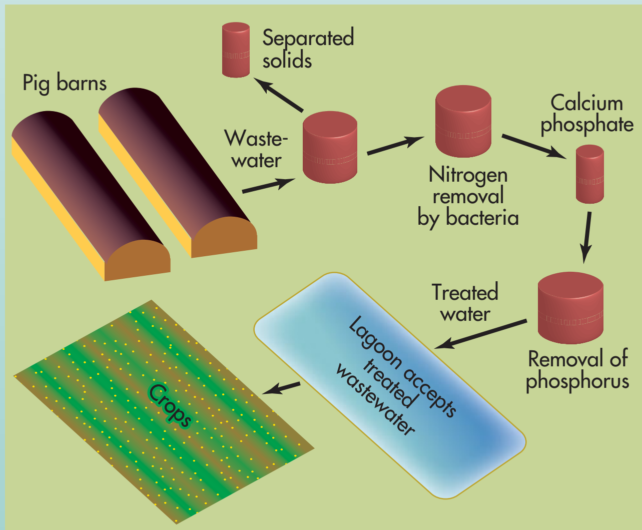


FIGURE 14.4 Treating pig waste onsite (a) Duplin County pig farm with treatment plant; (b) idealized diagram of how the treatment plant works.

14.1 An Overview of Water Pollution

Water pollution refers to degradation of water quality as measured by biological, chemical, or physical criteria. This degradation is judged according to the intended use of the water, its departure from the norm, and public health or ecological impacts. From a public health or ecological point of view, a **pollutant** is any substance that, in excess, is known to be harmful to desirable living organisms. In fact, *the primary water pollution problem facing billions of people today, especially in the developing world, is the lack of clean drinking water that is free of disease-causing organisms or substances.* The concentration at which a material becomes harmful to living things is the subject of toxicology, discussed in Chapter 19.

TABLE 14.1 Selected Chemicals That Agricultural, Industrial, and Municipal Processes Produce, Use, or Release to Impact Water Quality. Rates Are Millions (10^6) of Tons per Year

• *Nutrients in rivers of the world*	
Inorganic nitrogen	16
Phosphorus	3.4
• *Heavy metals in water systems*	
Mercury, lead, zinc, copper, cadmium, nickel, chromium	0.1–1
• *Global production of other chemicals affecting water qualities*	
Fertilizer	140
Synthetic organic chemicals	300
Oil spills	0.4

Source: Data from Schwarzenbach, R. P., et al. 2006. The challenge of micropollutants in aquatic systems. *Science* 313:1072–1077.

The greatest water pollution problem in the world today is lack of disease-free drinking water for about 20 percent of the world's population. Another 20 percent have poor sanitation conditions that favor waterborne diseases that kill about 2 million people a year. Most of the deaths are of children under age 5. Chemical pollution is also an emerging problem on a global scale that occurs almost every place where people live. Agricultural, industrial, and municipal processes release chemical pollutants whose long-term effects on the environment and human health are largely unknown.[4] **Table 14.1** lists annual releases (flux) of common chemicals that cause water pollution. Some of the pathways for water pollutants in the environment are shown in **Figure 14.5**.

14.2 Selected Water Pollutants

Many materials can pollute surface water or groundwater. Our discussion will focus on oxygen-demanding waste; pathogenic, or disease-causing, microorganisms; nutrients; oil; synthetic organic chemicals; heavy metals; radioactive materials; and sediment. We will also discuss a nonmaterial form of pollution: thermal pollution.

Oxygen-Demanding Waste

Dead plant and animal matter, called *organic matter*, in streams decays over time; that is, it is consumed by bacteria, which require oxygen. These are called *aerobic* bacteria, meaning they require oxygen to live. If there is enough bacterial activity, the oxygen in the water can be reduced to levels so low that fish and other organisms die. The amount of oxygen used for bacterial decomposition is the **biochemical oxygen demand (BOD)**, a commonly used measure in water-quality management. A high BOD indicates a high level of decaying organic matter in the water.

Dead organic matter in streams and rivers comes from natural sources, such as fallen leaves, as well as from agriculture and urban sewage. Approximately 33 percent of all BOD results from agricultural activities, but urban areas, particularly those with sewer systems that combine sewage and stormwater runoff, may add considerable BOD to streams during floods. Sewers entering treatment plants can be overloaded and overflow into streams, producing pollution.

Pathogenic Organisms

Pathogenic microbes or microorganisms, which are those that can be seen only with a microscope, are important biological pollutants. Cholera, typhoid infections, hepatitis, and dysentery are all waterborne diseases caused by pathogenic microorganisms. It is often difficult to monitor the pathogens directly; instead, the level of human *fecal coliform bacteria* is used as a common measure of biological pollution and as a standard measure of microbial

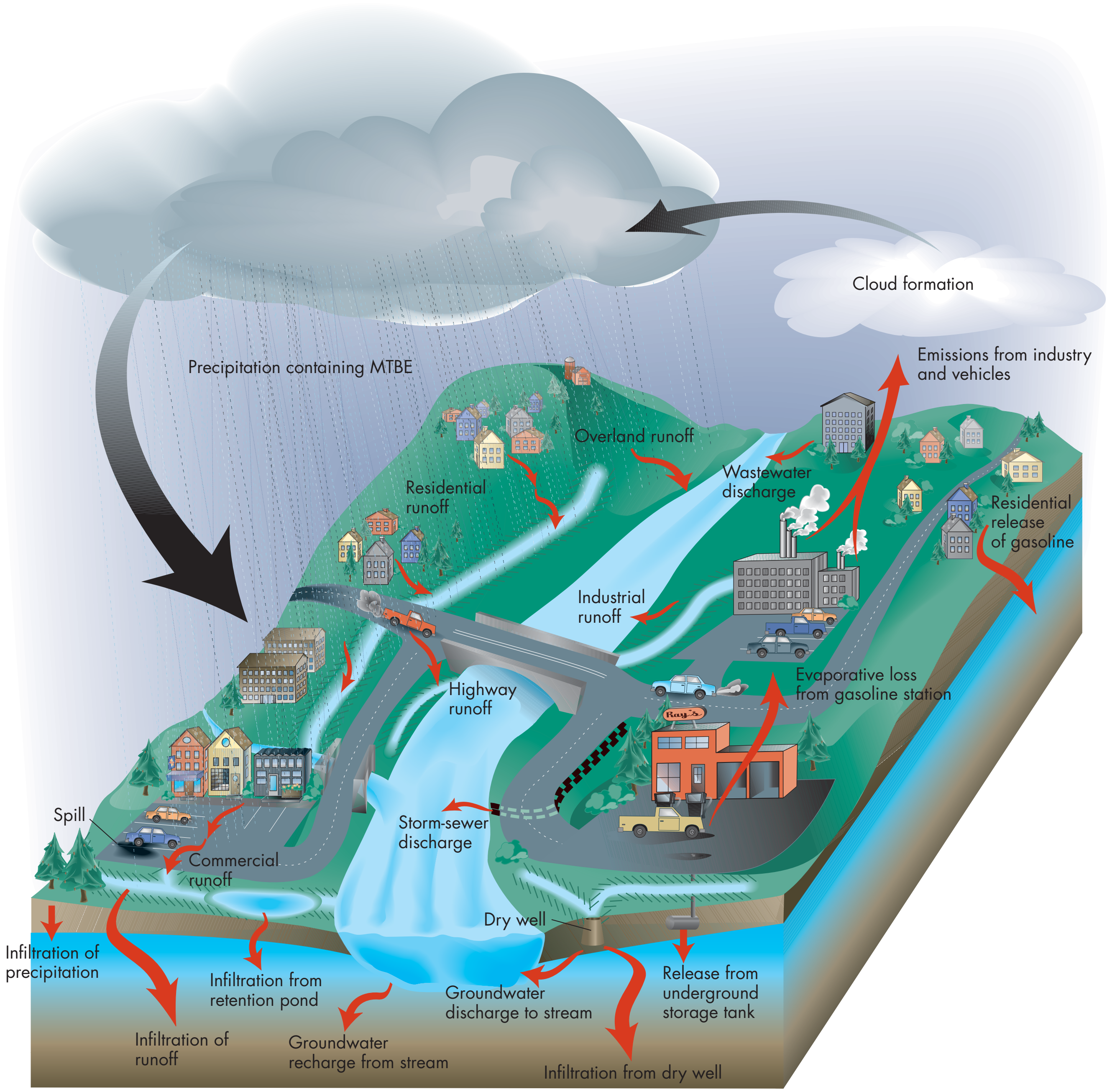


FIGURE 14.5 Pathways for chemical pollutants Diagram shows pathways for chemical pollutants within the hydrologic cycle of the environment. *(Modified from Delzer, G. C., Zogorski, J. S., Lopes, T. J., and Basshart, R. S. 1996.* Occurrence of Gasoline Oxygenate MTBE and BTEX Compounds in Urban Storm Water in the United States, 1991–95. *U.S. Geological Survey Water-Resources Investigation Report 96–4145)*

pollution. Fecal coliform bacteria are usually harmless, are part of the normal constituents of human intestines, and are found in all human waste.

However, not all forms of fecal coliform bacteria are harmless. *Escherichia coli* (also known as *E. coli* 0157), a strain of *E. coli* bacteria, has been responsible for human illnesses and deaths. *E. coli* 0157, which causes over 70,000 illnesses and 60 deaths in the United States each year, produces strong toxins in humans that may lead to bloody diarrhea,

dehydration, kidney failure, and death. In 1993, outbreaks of disease, apparently caused by *E. coli* 0157, occurred as a result of people's consumption of contaminated meat at a popular fast-food restaurant. In 1998, *E. coli* apparently contaminated the water in a Georgia water park and a Wyoming town's water supply, causing illness and one death.

One of the worst outbreaks of *E. coli* bacterial infection in Canadian history unfolded in May 2000 in Walkerton, Ontario. It is believed that the likely cause of the contamination in Walkerton was *E. coli* bacteria in cow manure washing into the public water supply during heavy rains and flooding that occurred on May 12, 2000. The local Public Utility Commission was aware as early as May 18 that water from wells serving the town was contaminated, but it did not report this contamination immediately to health authorities. As a result, people were not advised to boil water until it was too late to avoid the outbreak of disease. By May 26, 5 people had died, more than 20 were in the intensive care unit of the local hospital, and approximately 700 were ill with severe symptoms, including cramps, vomiting, and diarrhea. The old and very young are most vulnerable to the ravages of the disease, which can damage the kidneys, and 2 of the first victims of this outbreak were a 2-year-old baby and an 82-year-old woman. Government officials finally took over management of the water supply, and bottled water was distributed. Tragically, before the outbreak was over, at least 7 people had died and more than 1,000 had been infected. Study of people from the Walkerton breakout followed for several years after illness suggest they have an increased risk of hypertension (high blood pressure) and cardiovascular disease (hardening of the arteries).

Authorities launched an investigation, focusing on why there was such a long delay between identifying the potential problem and warning people. Had there not been such a long delay, illnesses might have been avoided. The real lesson learned from Walkerton is that we remain vulnerable to contamination of our water supply. We must remain vigilant in testing our waters and immediately report problems to public health authorities if any problems arise.

In the fall of 2006, *E. coli* 0157 was traced to farms in northern California. Contaminated spinach was shipped to 23 states. About 150 people became sick, and 1 person died. More recently, peanut butter contaminated with *E. coli* 0157 caused several hundred illnesses and killed several people across the United States in 2009.

Epidemics of waterborne diseases have killed thousands of people in U.S. cities. Such epidemics have been largely eliminated by separating sewage water and drinking water and treating drinking water before consumption. Unfortunately, this is not the case worldwide, and every year, several billion people, particularly in poor countries, are exposed to waterborne diseases. For example, an epidemic of cholera (explosive diarrhea and vomiting with serious dehydration, caused by the bacteria known as Vibrio cholerae) broke out in October of 2010 in Haiti. After the earthquake in January of 2010 over 1.3 million were forced into tent cities (especially near the capital city of Port-au-Prince). The crowded tent cities have very poor sanitation, and water pollution is a serious problem. A cholera epidemic claimed more than 3,000 lives (50,000 hospitalized) by early January 2011. Although developing nations are most vulnerable, the risk of waterborne diseases is a potential threat in all countries.

The threat of an outbreak of a waterborne disease is exacerbated by disasters such as earthquakes, floods, and hurricanes; these events can damage sewer lines or cause them to overflow, resulting in contamination of water supplies. For example, after the 1994 Northridge earthquake, people in the San Fernando Valley of the Los Angeles Basin were advised to purify municipal water by boiling because of the threat of bacterial contamination.

Nutrients

Nutrients released by human activity may lead to water pollution. Two important nutrients that can cause problems are phosphorus and nitrogen, both of which are released from a variety of materials, including fertilizers, detergents, and the products of sewage-treatment plants. The concentration of phosphorus and nitrogen in streams is related to land use. Forested land has the lowest concentrations of phosphorus and nitrogen, while the highest concentrations are found in agricultural areas, such as fertilized farm fields and feedlots. Urban areas can also add phosphorus and nitrogen to local waters, particularly where wastewater-treatment plants discharge treated

waters into rivers, lakes, or the ocean. These plants are effective in reducing organic pollutants and pathogens, but without advanced treatment, nutrients pass through the system.

High human-caused concentrations of nitrogen and phosphorus in water often result in the process known as **cultural eutrophication**. *Eutrophication* (from the Greek for "well fed"), a natural process, is characterized by a rapid increase in the abundance of plant life, particularly algae. Blooms of algae form thick mats that sometimes nearly cover the surface of the water in freshwater ponds and lakes. The algae block sunlight to plants below, and those plants eventually die. In addition, the algae consume oxygen as they decompose, thereby lowering the oxygen content of the water, and fish and aquatic animals may die as well.

In the marine environment, nutrients in near-shore waters may cause blooms of seaweed, referred to as marine algae, to flourish. The marine algae become a nuisance when they are torn loose and accumulate on beaches. Algae may also damage or kill coral in tropical areas. For example, the island of Maui in the Hawaiian Islands has a cultural eutrophication problem resulting from nutrients entering the near-shore environment from waste-disposal practices and agricultural runoff. Beaches in some areas become foul with algae that washes up on the shore, where it rots and creates a stench, providing a home for irritating insects that eventually drive away tourists (**Figure 14.6**).

A serious and ongoing cultural eutrophication problem is occurring in the Gulf of Mexico, offshore of Louisiana. A so-called dead zone (**Figure 14.7**) develops in the summer, over a large area about the size of New Jersey. Water in the zone has low concentrations of oxygen, killing shellfish and crabs, and blooms of algae occur. The cause of the cultural

(a)

FIGURE 14.6 Algae-contaminated beaches in Hawaii (a) Ocean-front condominium on the island Maui, Hawaii. The brown line along the edge of the beach is an accumulation of marine algae (locally called *seaweed*). (b) On the beach itself, the algae pile up, sometimes to a depth of about 0.5 m (1.7 ft), and people using the beach avoid the areas of algae piles. (c) Condominium complexes often have small wastewater-treatment plants, such as the one shown here, inside the plant-covered fence, that provide primary and secondary treatment. After this treatment, the water is injected underground at a relatively shallow depth. The treatment does not remove nutrients, such as phosphorus and nitrogen, that apparently encourage the accelerated growth of marine algae in the near-shore environment. *(Edward A. Keller)*

(b)

(c)

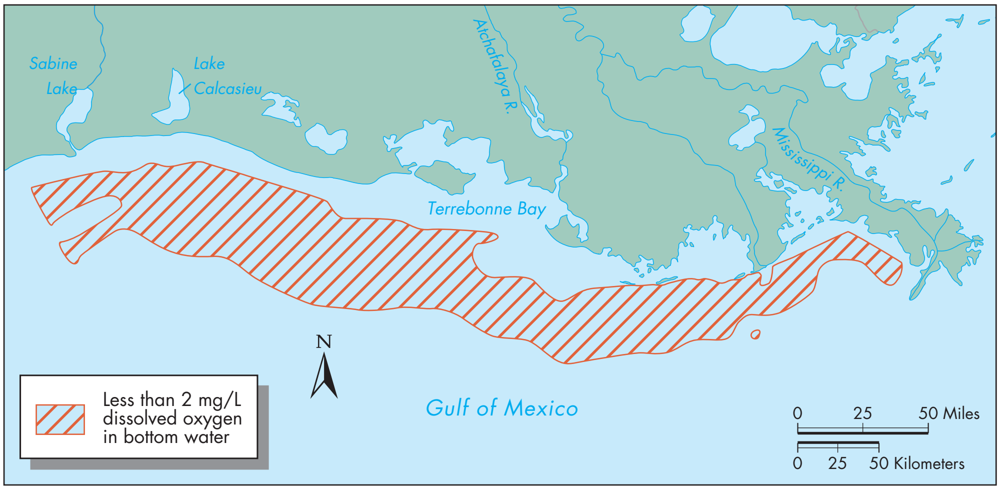


FIGURE 14.7 Dead zone in Gulf of Mexico Area in the Gulf of Mexico in July 2001 with bottom water with less than 2 mg/L dissolved oxygen. *(Modified after Rabalais, Turner, and Wiseman, 2001. Hypoxia Studies)*

eutrophication is believed to be the Mississippi River. The Mississippi drains about 40 percent of the lower 48 states, and much of the land use in the drainage basin is agricultural. The nutrient believed to cause the problem is nitrogen, which is used in great amounts to fertilize fields. The problem will not be easy to solve as long as agriculture continues to use tremendous amounts of fertilizer. Part of the solution will be modification of agricultural practices to use less nitrogen by using it more efficiently so that less of the nutrient runs off the land into the river.[5] Numerous other areas around the world, often just offshore of large urban or agriculture regions, with significant discharge of nutrients into the ocean have cultural eutrophication similar to that in the Gulf of Mexico.

Oil

Oil discharged into surface water (i.e., rivers, lakes, and the ocean) has caused major pollution problems. The largest oil discharges have usually involved oil-tanker accidents at sea. For example, just after midnight on March 24, 1989, the oil tanker *Exxon Valdez* ran aground on Bligh Reef, 40 km (25 mi) south of Valdez, Alaska, in Prince William Sound. Crude oil poured out of the ruptured tanks of the vessel at a rate of approximately 20,000 barrels per hour (**Figure 14.8**). The *Exxon Valdez* was loaded with 1.2 million barrels of crude oil, and, of this, more than 250,000 barrels (11 million gal) gushed from the hold of the 300 m (984 ft) tanker. The oil remaining in the *Exxon Valdez* was loaded into another tanker.[6]

The oil spilled into what *was* considered one of the most pristine and ecologically rich marine environments of the world, and the accident is now known as one of the worst oil spills in the history of the United States. Short-term impacts were very significant. Commercial fisheries, sport fisheries, and tourism were disrupted. In addition, many seabirds and mammals were lost. Lessons learned from the *Exxon Valdez* spill have resulted in better management strategies for both the shipment of crude oil and emergency plans to minimize environmental degradation.

A large oil spill in 2006 was caused by the war in Lebanon, when a coastal power plant was bombed and over 100,000 barrels of fuel oil entered the Mediterranean Sea. Over half of Lebanon's tourist beaches were polluted, including a popular public beach visited by people from the capital city Beirut.

Most previous spills were relatively small compared to the Gulf spill in the summer of 2010. On April 20, 2010, an exploratory oil well was being completed prior to production on the Deepwater Horizon platform off the shore of the Mississippi River delta in about 1,500 m (5,000 ft) of water. The well was drilled another 3,000 m (15,000 ft) into the rocks of the Gulf. The floating oil platform was very

(a) (b)

FIGURE 14.8 Oil spill from the *Exxon Valdez* in Alaska, 1989 (a) Aerial view of oil being offloaded from the leaking tanker *Exxon Valdez* on the left to the smaller *Exxon Baton Rouge* on the right. Floating oil is clearly visible on the water. *(Natalie Fobes/Corbis)* (b) Attempting to clean oil from the coastal environment by scrubbing and spraying with hot water. *(I. L. Atlan/Corbis)*

FIGURE 14.9 Deepwater Horizon oil-drilling platform on fire The blowout and fire in the spring of 2010 started the largest oil spill in U.S. history. *(U.S. Coast Guard/Getty Images)*

large and extremely complex, kept in place by navigation using Global Position Satellite systems. The well was in the process of being fitted with a cement plug when a large volume of methane gas evidently escaped the systems designed to suppress a blowout (i.e., uncontrolled release of gas and oil that occurs after systems to control pressure fail) and enveloped the platform. The time between when the gas moved up from the bottom of the sea to the platform and when the platform burst into flames was probably only a few minutes (**Figure 14.9**). The explosion and fires killed 11 workers and injured many others, who escaped to lifeboats. The result was an *oil spill*, defined as an accidental release of oil into the environment as a result of human activities on an oil rig, from failure of a tanker ship transporting oil, or the failure of an oil pipeline. The platform burned and sank to the bottom of the sea. As part of

the completion process, a decision was made to remove the drilling mud (i.e., very heavy fluids) used to counteract the natural pressure from the subsurface. In other words, the heavy drilling mud helps keep formation fluids (i.e., water, oil, and natural gas) in the well in place and from rising to the surface. If the oil and gas pressure is not contained by a functioning blowout preventer, it will rush out and up through the water to the surface. It is believed that that decision to withdraw the heavy drilling mud shortly before the blowout was the major mistake that resulted in the blowout; without the mud and with the blowout preventer malfunction, there was only water pressure to keep the oil and gas from escaping, and that was a recipe for disaster. Even prior to the blowout, there were reported problems with the well, and workers and others expressed concerns about being able to control the well (i.e., prevent an incident in which oil would escape into the environment). The natural subsurface pressure is several times the pressure of the overlying water, and, so, when the blowout occurred, water, oil, and natural gas moved quickly through 1,500 m (5,000 ft) of ocean water to the surface. Another technical problem arose because, when the fire on the platform occurred, equipment designed to possibly control what was going on at depth was destroyed. An automatic shutoff was a safety feature that was supposed to stop the flow of oil if something happened to the rig. However, because the rig was on fire, the sophisticated navigation equipment that kept the floating platform in place and supported the safety feature was destroyed by the fire. The navigation equipment is critical in keeping the pipe, which contains the oil, directly over the well itself in the bottom of the seabed. Movement of the platform severed that pipe, and oil was released as a spill.

The amount of oil actually released remains controversial, most likely varying from about 20,000 to 60,000 barrels per day (1 barrel = 42 gal). The amount of oil released into the Gulf before the leak was finally stopped was about 5 million barrels (20 times that of the Exxon Valdez discussed earlier). That's a lot of oil to be released into the marine environment. Released with the oil was a large amount of natural gas, and this natural gas was mostly responsible for the explosion and fire that destroyed the platform. Much of the methane in the water column is acted upon by bacteria and degraded.

The response to the oil spill was immediate and consisted of practices used in past spills. Time was of the essence because oil spills can be toxic and harmful to marine life, including birds, reptiles, and mammals. The oil can also harm fish and shellfish.

The location of the Deepwater Horizon platform is shown in **Figure 14.10**, along with nearly 4,000 other platforms in the Gulf region in the coast off the United States. By mid-June 2010, oil from the spill had reached a number of beaches and wetlands along the coasts of Louisiana and Alabama. The amount of oil released and reactions with wind, current, and tides in the Gulf will determine the spread of the oil in the future.[7]

A variety of methods have been used to try to control the spread of oil and clean it up after it has

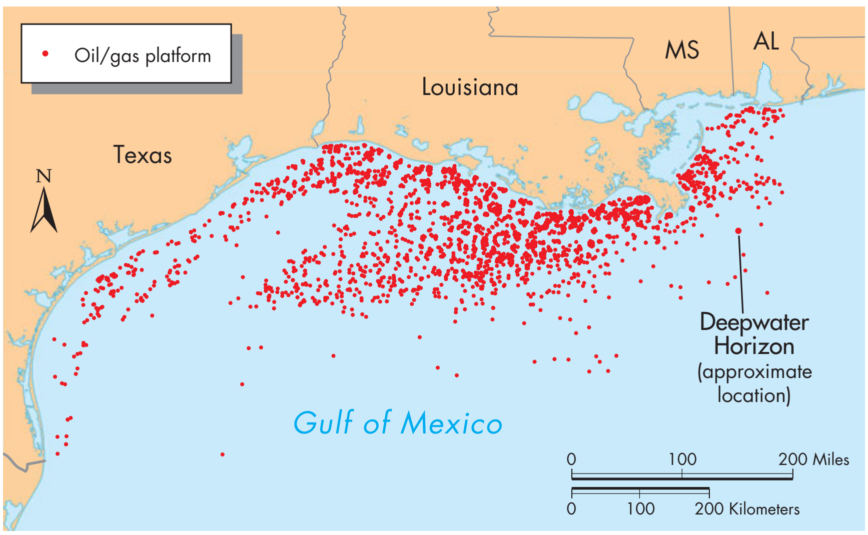


FIGURE 14.10 Oil-drilling platforms in the Gulf of Mexico Map shows locations of approximately 4,000 platforms in the Gulf of Mexico.

(a)

(b)

FIGURE 14.11 Oil on the shore Wetlands (a) and beaches *(Julie Dermansky/Corbis)* (b) were polluted by oil spilled by the blowout of a well on the Deepwater Horizon platform during the summer of 2010. *(Julie Dermansky/Corbis)*

made landfall at a beach or wetland (**Figure 14.11**). Most of these methods have been around for decades, and the technology has not improved much during this period. The methods include deploying booms, skimmers, and chemical dispersants; burning the oil in water in situ; washing the oil off beaches; and vacuuming or picking up the oil. Sometimes, equipment as simple as shovels and road equipment is used to pick up oil from sandy beaches. The particular methods used depend upon the site, how much oil is present, and the accessibility of the site to necessary equipment.[7] Wildlife both in the Gulf and on shore was impacted by the Deepwater Horizon oil spill. Sea birds and turtles were taken to refuge locations where they were cleaned and cared for in hopes that they might be released into the environment in the future.[8,9]

The oil spill in the Gulf of Mexico is the worst such disaster in the history of the United States. It is feared that the consequences of the spill will be chronic, lasting several years. Fishermen were put out of work as the Gulf waters were partially closed to fishing. People in tourist areas lost money because travelers began picking other locations, not wanting to contend with oil on beaches. Supporting businesses related to fishing and tourism also suffered financially. As a result, the company responsible for the cleanup has agreed to post a $20 billion escrow fund to be dispersed by the U.S. government to those who need assistance and were affected financially by the spill.

What we have learned from the Deepwater Horizon oil spill is, first, that it should never have happened. It was a human-caused spill and should have been preventable. You can argue that there are thousands of platforms in the Gulf of Mexico, and, so, the probability of one experiencing a blowout is very low. However, the risk from an environmental event is the product of that event multiplied by the consequences. The probability of the blowout may have been small, but the consequences are very large. We must recognize, though, that no matter how careful we are and how good our technology is, accidents can happen.

The response to the oil spill was reactive. A great number of boats (about 6,000) were deployed, with about 25,000 workers, to try to minimize the spread of the spill and collect oil in the sea and on land. Some oil was burned, and chemical dispersants were applied from aircraft, as well as at the bottom of the sea, where the leak was occurring. These dispersants are chemicals and themselves have environmental impacts. It is known that these chemicals can damage marine ecosystems, but some scientists, at the time of the spill, looked at using or not using dispersants as a case of which was the lesser of two evils. Dispersants were used, but the long-term impact of them, particularly on the sea bed, is largely unknown. This brings up an important point: The science of the deep-ocean basin has not progressed significantly to be able to adequately predict the processes there and how they will interact with the oil and dispersants. At the surface, we know that the oil moves with the currents and the winds and ends up on some shore lines, where it does ecological damage. We then use antiquated systems of collection.[9]

What could have been done better in the Deepwater Horizon spill? First of all, we need adequate

regulation of the oil industry to ensure that all safety practices are followed carefully, and research needs to be done to make the blowout prevention devices more fail-safe. First, to be proactive about future oil spills, we need to do everything possible to ensure that they do not happen. Second, we need to be more proactive in planning what to do after a spill. Big oil spills happen rather infrequently, and, as a result, between spills, technology may not go forward in anticipation of the next spill. The bottom line is that we need to be much more proactive about oil spills rather than reactive. Following a spill, we have no choice but to be reactive, but the real work should be done before a spill ever occurs in order to prevent spills and deal with them in a timely way.

Will the Gulf recover from the 2010 oil spill? Certainly, it will. Oil is a nutrient, in both the water and the near-shore environment. The recovery so far has been more rapid than expected. However, the *Exxon Valdez* spill has shown us that some oil remains even decades following spills. The Gulf may therefore be a changed environment for a number of years. The spill will continue to have adverse effects on ecosystems and on people's livelihoods. To some extent, this is a natural experiment, as we have no previous experience in dealing with such large spills that places oil and dispersants at the bottom of the deep sea, as well as oil on beaches and in salt marshes. Hopefully, we will learn from this experience and reduce the chances of future spills. Given the best technology and the best engineering, human error will surely be responsible for spills on land and in the ocean in the future. However, we can be more proactive in minimizing their effects.

Toxic Substances

Many substances that enter surface water and groundwater are toxic to organisms. We will discuss three general categories of toxic substances—synthetic organic chemicals, heavy metals, and radioactive waste.

Synthetic Organic Chemicals. Organic compounds are compounds of carbon that are produced naturally by living organisms or synthetically by industrial processes. Up to 100,000 new chemicals are now being used or have been used in the past. It is difficult to generalize concerning the environmental and health effects of synthetic organic compounds because there are so many of them, and they have so many uses and produce so many different effects.

Synthetic organic compounds have many uses in industrial processes, including pest control, pharmaceuticals, and food additives. Some of these compounds are called *persistent organic pollutants*, also known as *POPs*. Many of these chemicals were produced decades ago, before their harm to the environment was known, and a number have now been banned or restricted. **Table 14.2** lists some of the common persistent organic pollutants and their uses. Several general properties are useful in defining POPs.[10] First, POPs have a carbon-based structure and often contain reactive chlorine. Second, most are produced by human processes and, thus, are synthetic chemicals. Third, they persist in the environment, do not break down easily, are polluting and toxic, and tend to accumulate in living tissue. Fourth, they occur in a number of forms that allow them to be easily transported by water and wind with sediment for long distances.

A significant example of a water polluter is the chemical MTBE (methyl tert-butyl ether). The Clean Air Act Amendments that were passed in 1990 required cities with air pollution problems to use what are known as "oxygen additives" in gasoline. MTBE is added to gasoline with the objective of increasing the oxygen level of the gasoline and decreasing

TABLE 14.2 Selected Persistent Organic Pollutants (POPs)

Chemical	Example of Use
Aldrin[1]	Insecticide
Atrazine	Herbicide
DDT[1]	Insecticide
Dieldrin[1]	Insecticide
Endrin[2]	Insecticide
PCBs[1]	Liquid insulators in electric transformers
Dioxins	By-product of herbicide production

[1]Banned in the United States and many other countries.

[2]Restricted or banned in many countries.

Data in part from McGinn, Anne Platt, "Phasing Out Persistent Organic Pollutants," in Lester R. Brown, et al., *State of the World 2000* (New York: Norton, 2000).

emissions of carbon monoxide from gasoline-burning cars. It is used because MTBE is more economical than other additives, including alcohol. MTBE is very soluble in water and is a commonly detected volatile organic compound (VOC) in urban groundwater. It is hypothesized that the MTBE detected in shallow groundwater originates from three sources: urban stormwater runoff, leaking underground gasoline tanks, and leakage occurring at service stations when car tanks are being filled.

It is ironic that a gasoline additive intended to improve air quality is now contaminating the groundwater that is used as a source of drinking water for approximately 15 million people in California. In 1997, MTBE-polluted groundwater in Santa Monica, California, forced the city to stop pumping groundwater, eliminating approximately 50 percent of the total drinking water supply for the city. Concentrations of MTBE in Santa Monica's groundwater ranged from about 8 to 600 micrograms (μg) per liter. The Environmental Protection Agency has stated that concentrations of 20 to 40 μg of MTBE per liter of water are sufficient to cause objectionable taste and odor. MTBE in that concentration smells like turpentine or fresh paint and is nauseating to some people. Studies are under way concerning the toxicity of MTBE, and some researchers fear that it is a carcinogenic chemical (i.e., capable of causing or promoting cancer). As a result of the contamination, some states, such as California, have terminated the use of MTBE. See Figure 14.5 for some of the pathways of MTBE, as well as other volatile organic compounds, in the hydrologic cycle of an urban area.[11]

Heavy Metals. Heavy metals, such as lead, mercury, zinc, cadmium, silver, and arsenic, are dangerous pollutants that are often deposited with natural sediment in the bottoms of stream channels. If these metals are deposited on floodplains, they may become incorporated into plants, including food crops, and animals. Once the metal has dissolved in water used for agricultural or domestic use, heavy-metal poisoning can result.

As an example, consider mercury contamination of aquatic ecosystems. It has been known for decades that mercury is a significant pollutant of aquatic ecosystems, including ponds, lakes, rivers, and the ocean.[12]

Perhaps the best-known case history of mercury toxicity comes from Minamata, Japan. Minamata is a coastal town on the island of Kyushu and was the site of a serious illness that was first recognized in the middle of the twentieth century. It was first called the *disease of the dancing cats* because the illness was first observed in cats that seemingly went mad and ran in circles, foaming at the mouth. It was also noticed that birds flew into buildings or fell to the ground. People were subsequently affected, and most were families of fishermen. Some of the first symptoms were fatigue, irritability, numbness in arms and legs, and headaches, as well as difficulty swallowing. Some of the more severe symptoms included blurred vision, loss of hearing, and loss of muscular coordination. Some people complained of a metallic taste in their mouths and suffered from diarrhea. By the time the disease ran its course, more than 40 people died and more than 100 were severely disabled. The people affected by the disease lived in a relatively small area, and their diet mostly consisted of fish harvested from Minamata Bay.

The disease was eventually traced to a vinyl chloride factory on Minamata Bay that used mercury in its production processes. Inorganic mercury was released as waste into the bay, and it was believed that the mercury would not get into the food chain. However, the inorganic mercury was converted by bacterial activity in Minamata Bay to methylmercury (discussed in more detail later in the chapter). Methylmercury readily passes through cell membranes and is transported throughout the body by red blood cells. It can enter and damage brain cells. The harmful effects of methylmercury depend on a number of factors, including the amount of exposure and intake, the duration of the exposure, and the species affected. The effects of the mercury are often delayed from several weeks to months in people from the time of ingestion. Furthermore, if the intake of mercury ceases, some of the symptoms may disappear, but others are difficult to reverse.[12]

The disease of the dancing cats eventually became known as Minamata disease, and nearly 800 people were officially recognized as having the disease, but as many as several thousand may have been involved. The mercury pollution in the bay ceased in 1968. As recently as the 1990s, some of the people afflicted by the disease were still being compensated for damages.

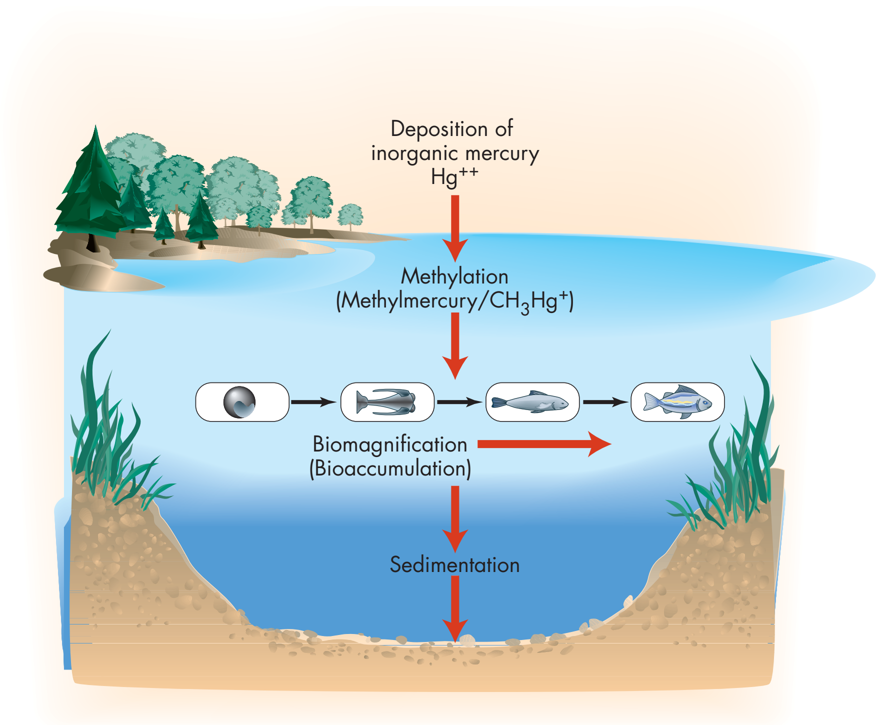


FIGURE 14.12 Mercury in the environment Input and changes of mercury in aquatic ecosystems. *(Modified from U.S. Geological Survey. 1995.* Mercury Contamination of Aquatic Ecosystems. *U.S. Geological Survey Fact Sheet FS-216-95)*

There are several natural sources of mercury, including input from volcanoes and erosion of natural mercury deposits. In most cases, however, we are most concerned with the input of mercury into the environment through processes such as burning coal, incinerating waste, and processing metals. Although the rates of mercury input into the environment by humans are poorly understood, it is believed that human activities have doubled or tripled the amount of mercury in the atmosphere, and it is increasing at about 1.5 percent per year.[13] Deposition from the atmosphere through rainfall is the primary source of mercury in most aquatic ecosystems. Once ionic mercury (Hg^{2+}) is in surface water, it enters into complex cycles, during which a process known as methylation may occur. Bacterial activity changes the inorganic mercury to methylmercury (CH_3Hg^+). This process is important from an environmental viewpoint because methylmercury is much more toxic than ionic mercury. Furthermore, living things require longer periods of time to eliminate methylmercury from their systems than they do to eliminate inorganic mercury. As the methylmercury works its way through food chains, a process known as *biomagnification* occurs in which concentrations of methylmercury increase in higher levels of the food chain. Thus, big fish in a pond contain higher concentrations of mercury than do the smaller fish and aquatic insects that the large fish feed upon. Some aspects of the mercury cycle in aquatic ecosystems are illustrated in Figure 14.12. The input side of the mercury cycle shows the deposition of inorganic mercury through the formation of methylmercury. On the output side of the cycle, mercury entering fish may be taken up by the organism that eats the fish (Figure 14.13). Sediment may also release mercury by a variety of processes, including resuspension in the water; this can eventually result in the mercury's entering the food chain or being released back into the atmosphere through volatilization, the process of converting a liquid or solid to a vapor.

Arsenic is an example of a highly toxic natural metal that is found in soil, rock, and water. There are many industrial and commercial uses of arsenic compounds, including the processing of glass, pesticides, and wood preservatives. Arsenic may enter our water supplies through a number of processes, including natural rain, snowmelt, or groundwater flow. It may also be released with industrial wastewater and agricultural processes. Finally, it may be released through the production of pesticides, the burning of fossil fuels, and as a by-product of mining.

FIGURE 14.13 Fish may contain toxic metals People cooking and eating fish, here in the Fiji Islands, take in chemicals, including metals that the fish have in their tissue. Mercury is a potential problem with fish such as tuna and swordfish. *(Peter Arnold Inc.)*

Arsenic has been known as a deadly poison since ancient times, and, more recently, it has been recognized that elevated levels of arsenic in drinking water may cause a variety of health problems that affect organs, such as the bladder, lung, and kidney. It may also cause disease to the central nervous system. Finally, arsenic is known to be a carcinogen.

The occurrence of arsenic in drinking water is now recognized as a global problem. Arsenic certainly is not found in all water supplies, but it is found in many around the world. For example, arsenic in groundwater in Bangladesh has affected many millions of some of the poorest people on Earth. Ongoing research has aimed to identify those locations where arsenic pollution occurs and to develop appropriate technology or methods to avoid or reduce the hazard of exposure to arsenic.[14]

Radioactive Waste. Radioactive waste in water may be a dangerous pollutant. Environmentalists are concerned about the possible effects of long-term exposure to low doses of radioactivity to people, other animals, and plants (see Chapter 16).

Sediment

Sediment consists of unconsolidated rock and mineral fragments, the smallest of which range in size from sand particles to very small silt- and clay-sized particles. These small particles cause most sediment pollution problems. Sediment is our greatest water pollutant by volume; it is clearly a resource out of place. It depletes soil, a land resource; can reduce the quality of the water resource it enters; and may deposit undesired materials on productive croplands or on other useful land. Sediment pollution is discussed in detail in Chapter 17.

Thermal Pollution

Thermal pollution is the artificial heating of waters, primarily by hot-water emission from industrial operations and power plants. Heated water causes several problems. First, heated water contains less oxygen than cooler water; even water only several degrees warmer than the surrounding water holds less oxygen. Second, warmer water favors different species than does cooler water and may increase the growth rates of undesirable organisms, including certain water plants and fish. In some cases, however, the warm water may attract and allow better survival of certain desirable fish species, particularly during the winter.

14.3 Surface-Water Pollution and Treatment

Pollution of surface waters occurs when an excess of an undesirable or harmful substance flows into a body of water and exceeds the natural ability of that ecosystem to utilize, remove, or convert the pollutant to a harmless form. Water pollutants are emitted from localized sources, known as point sources, or by diffuse sources, known as nonpoint sources.

Point Sources of Surface-Water Pollution

Point sources are discrete and confined, such as pipes that empty into streams or rivers from industrial or municipal sites (Figure 14.14). In general, point-source pollutants from industries are controlled through on-site treatment or disposal and are regulated by permit. Municipal point sources are also regulated by permit.

FIGURE 14.14 Point source Pipe discharging partially treated waste from the Climax Molybdenum Mine in Colorado. Point sources are restricted and controlled by law in the United States. *(Jim Richardson/Richardson Images Ltd.)*

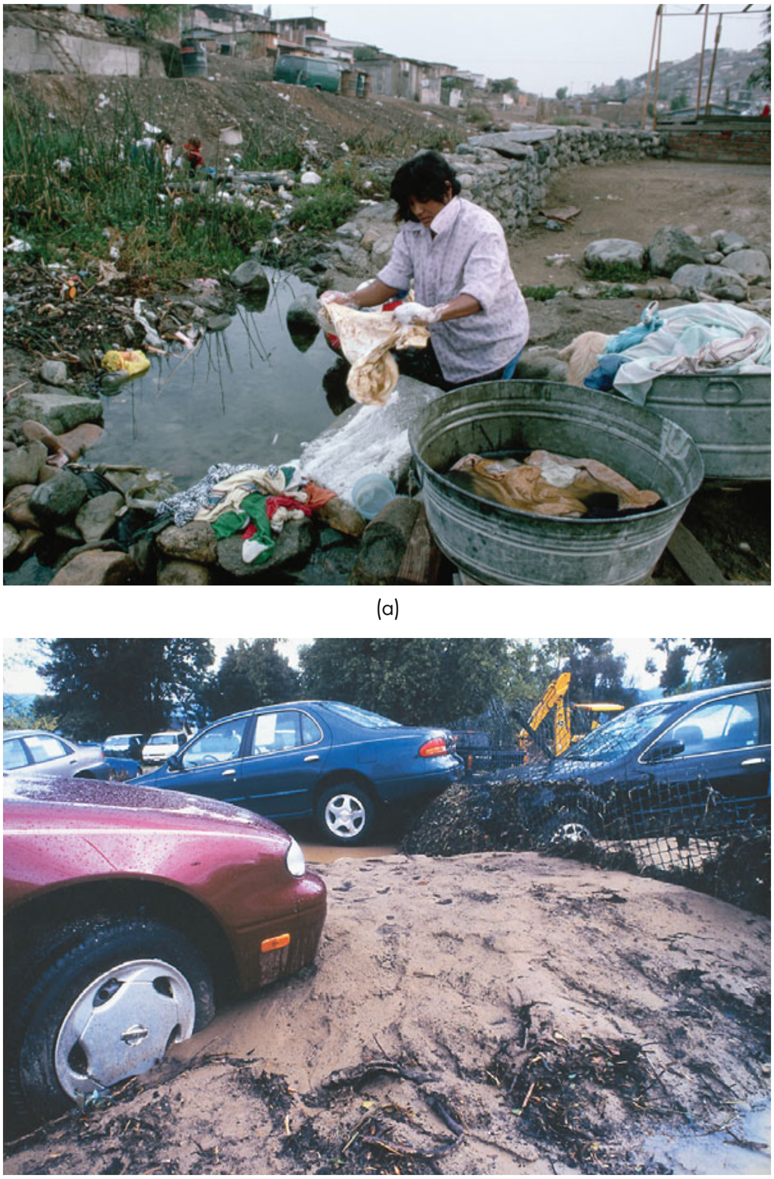
Nonpoint Sources of Surface-Water Pollution

Nonpoint sources are diffuse and intermittent; they are influenced by such factors as land use, climate, hydrology, topography, native vegetation, and geology. Common urban nonpoint sources include runoff from streets or fields. Rural sources of nonpoint pollution are generally associated with agriculture, forestry, or mining (see A Closer Look: Acid Mine Drainage).

Pollution from nonpoint sources, or polluted runoff, is difficult to control and contains all sorts of pollutants, from heavy metals to chemicals and sediment (**Figure 14.15**). Even when you wash your car in your driveway and the detergent and oil on the surface run down a storm drain that enters a stream, you are contributing to polluted runoff. Polluted runoff is also produced when rainwater washes insecticides from the plants in your garden, then runs off into a stream or infiltrates the surface to contaminate groundwater. Similarly, rain and runoff from factories and storage yards are a source of nonpoint pollution.[15]

Reduction of Surface-Water Pollution: The Cuyahoga River Success Story

In the United States, a concerted effort is underway to reduce water pollution and thereby improve water quality. The assumption is that people have a basic right to safe water for drinking, swimming, and use in agriculture and industry. At one time, water quality near major urban centers was considerably worse than it is today. Consider the story of the Cuyahoga River. The continental glacial ice sheets that formed the Great Lakes last receded from the United States over 10,000 years ago. In what is now northern Ohio, a river formed, flowing into what was later named Lake Erie. Native Americans who arrived over 2,000 years ago in the Ohio Valley named the river Cuyahoga, which, in their language, meant a meandering river (i.e., having a sinuous form with many bends). The river was of great use to the early Native Americans who lived along the river and depended on it as a natural route for transporting goods that they consumed and traded with other people. In the seventeenth and



(a)

(b)

FIGURE 14.15 Examples of nonpoint-source water pollution (a) Severe water pollution producing a health hazard. This ditch carries sewage and toxic waste to the Rio Grande in Mexico. *(Annie Griffiths Belt/Corbis)* (b) Sediment being removed by heavy equipment (shown in the background) after a 1995 flood in Goleta, California. The sediment came from a nearby stream that overflowed its banks and deposited it in the lot of a new car dealership. *(Rafael Moldanado/Santa Barbara News-Press)*

eighteenth centuries, fur traders arrived from Europe to trade with the Native Americans, and the War of 1812 displaced Native Americans from the Cuyahoga Valley. A few decades later, industrialization arrived in the river valley, and canals that linked the river to Lake Erie were constructed; in their time, they carried a tremendous volume of freight. With the growth of industrialization of the river valley and, in particular, the city of Cleveland, Ohio, pollution of the river became more and more common. At that time, laws to prohibit the dumping of waste into the river did not exist, and, with the arrival of the petroleum industry in Cleveland, the river became even more polluted. As a result of the pollution, fish and other living things in the river died, and the river became one of the most polluted in the United States. In 1969, the Cuyahoga River made environmental history when sparks from a train ignited oil floating on the water in the river, setting the surface of the river on fire! The burning of an American river became a rallying point for growing environmental consciousness.

The Cuyahoga River today is cleaner and is no longer flammable.[16] Parts of the river have been transformed into a greenbelt that has changed the river from an open sewer to a valuable public resource, as well as a focal point for economic and environmental renewal. However, in downtown Cleveland and Akron, the river remains an industrial stream, and parts are still polluted. Large portions of the upper part of the river have been designated as a State of Ohio Scenic River, and the Cuyahoga Valley National Recreation Area is sited in the valley between the cities of Cleveland and Akron. Finally, portions of the middle and lower river valley were designated as National Heritage Sites. What will be the final outcome for the Cuyahoga River and its scenic valleys and urban areas? It seems that the river system is much revered by the people of Ohio, and the river, hopefully, will continue to be a showcase of positive river restoration, demonstrating how even very polluted rivers may be restored.

Urban Flooding and Water Pollution

During periods of surface runoff and flooding, pollutants such as sediment, organic waste, pesticides, oil, and infectious agents from urban land may enter

A Closer Look

Acid Mine Drainage

Acid mine drainage refers to acidic water with elevated concentrations of dissolved metals that drains from coal or metal mines. Specifically, acid mine drainage is water with a high concentration of sulfuric acid (H_2SO_4) that drains from some mining areas to pollute surface-water resources. Acid mine drainage is produced by complex geochemical and microbial reactions when sulfide minerals associated with coal or a metal, such as zinc, lead, or copper, come into contact with oxygen-rich water near the surface. For example, pyrite (FeS_2) is a common sulfide often associated with coal; when pyrite oxidizes in the presence of water and microbes, sulfuric acid is formed. The sources for the water may be surface water that infiltrates into mines or shallow groundwater that moves through mines. Similarly, surface and shallow groundwaters that come into contact with mining waste, called tailings, may also react with sulfide minerals found there to form acid-rich waters.

Once waters with a high concentration of sulfuric acid and dissolved metals migrate away from a mining area, they can pollute surface and groundwater resources. If the acid-rich water runs into a natural stream or lake, significant ecological damage may result. The acid water is extremely toxic to plants and animals in aquatic ecosystems; acidic waters may also mobilize other potentially harmful chemicals. Acid mine drainage is a significant water pollution problem in many parts of the United States, including parts of Wyoming, Illinois, Indiana, Kentucky, Tennessee, Missouri, Kansas, Oklahoma, West Virginia, Maryland, Pennsylvania, Ohio, and Colorado. The total impact of acid mine drainage is significant; thousands of kilometers of streams have been polluted (**Figure 14.A**).

The Tar Creek area of Oklahoma was at one time designated by the Environmental Protection Agency as the nation's worst example of acid mine drainage. The creeks in the area were severely polluted by acid-rich water from abandoned mines in the Tri-State Mining District of Kansas, Oklahoma, and Missouri. Sulfide deposits containing both lead and zinc were first mined there in the late nineteenth century, and mining ended in some areas in the 1960s. During operation of the mines, subsurface areas were kept dry by pumping out groundwater that was constantly seeping in. After mining stopped, the groundwater tables naturally rose again. Subsequently, some of the mines flooded and overflowed, polluting nearby streams. The Tri-State Mining District remains an area of concern, and a lot of work has been done to reduce the impact of mines. The likely solution to reducing acid mine drainage in Tar Creek and other areas in the region is to use passive methods of treatment that utilize naturally occurring chemical and/or biological reactions in controlled environments to treat acid mine drainage. The simplest controlled environment is an open limestone channel. The acid-rich water reacts with crushed limestone, and the acid is neutralized.

FIGURE 14.A Acid mine drainage Water seeping from this Colorado mine is an example of acid mine drainage. The water is also contaminated by heavy metals, including iron compounds that produce the orange color. *(Tim Haske/Profiles West/Photolibrary)*

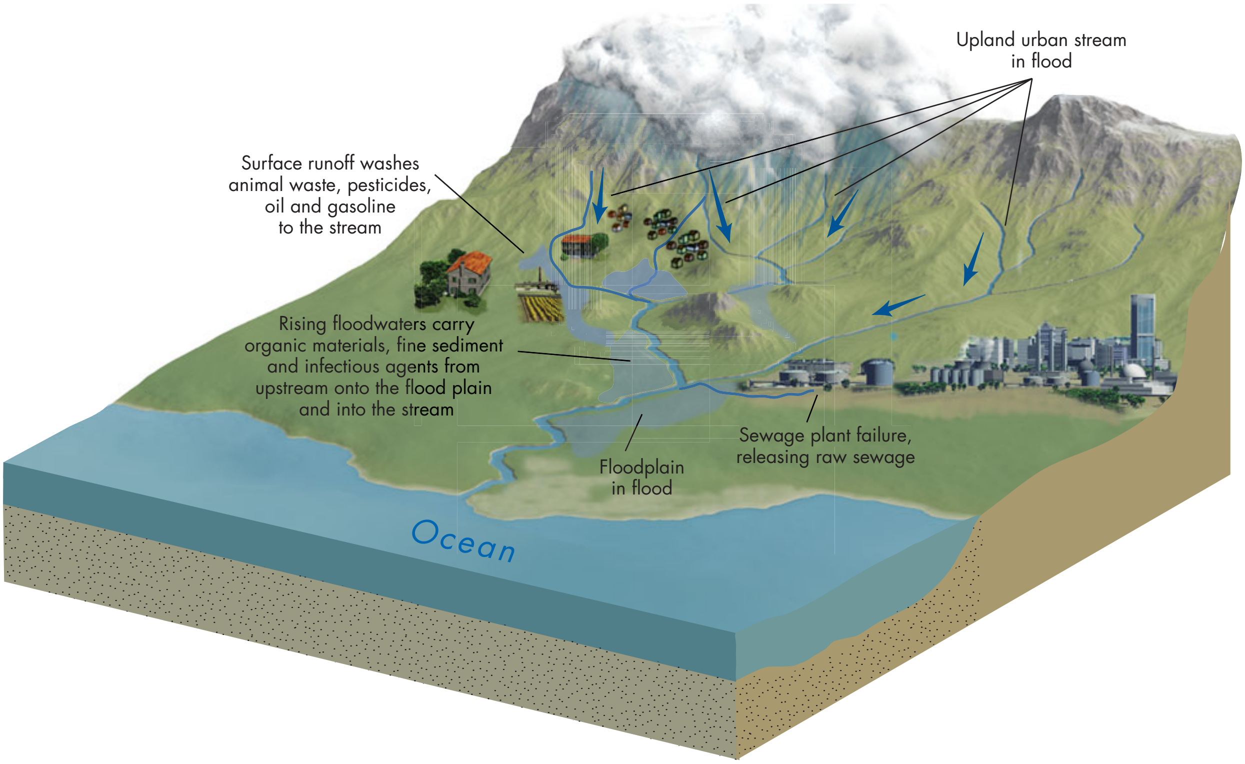


FIGURE 14.16 Urban flooding and water quality Idealized diagram showing the relationship between urban flooding and water quality.

local streams. In addition, wastewater treatment plants may be overwhelmed by the runoff of flooding and fail, sending raw waste into streams (**Figure 14.16**). As a result, areas downstream receive polluted water. Towns and cities along the stream or river that use the water may have water quality problems.

14.4 Groundwater Pollution and Treatment

Approximately one-half of all people in the United States depend on groundwater as their source of drinking water. We are, therefore, concerned about the introduction into aquifers of chemical elements, compounds, and microorganisms that do not occur naturally within the water. The hazard presented by a particular groundwater pollutant depends on several factors, including the volume of pollutant discharged, the concentration or toxicity of the pollutant in the environment, and the degree of exposure of people or other organisms.

Most of us have long believed that our groundwater is pure and safe to drink, and many of us find it alarming to learn that it may be easily polluted by any one of several sources (**Table 14.3**). In addition, even the very toxic pollutants may be difficult to recognize.

Currently, the problem of groundwater pollution in the United States is becoming more apparent as water testing becomes more common. For example, Atlantic City, New Jersey, and Miami, Florida, are two eastern cities threatened by polluted groundwater that is slowly migrating toward their wells. It is estimated that 75 percent of the 175,000 known waste-disposal sites in the country may be producing plumes (elongated bodies of contaminated groundwater). Many of the chemicals found in our groundwater are toxic or suspected carcinogens. It therefore appears that we have been conducting a national large-scale experiment concerning the effects of chronic low-level exposure of people to

TABLE 14.3 Common Sources of Groundwater Pollution and Contamination

Leaks from storage tanks and pipes
Leaks from waste-disposal sites such as landfills
Seepage from septic systems and cesspools
Accidental spills and seepage (e.g., train or truck accidents)
Seepage from agricultural activities such as feedlots
Intrusion of saltwater into coastal aquifers
Leaching and seepage from mine spoil piles and tailings
Seepage from spray irrigation
Improper operation of injection wells
Seepage of acid water from mines
Seepage of irrigation return flow
Infiltration of urban, industrial, and agricultural runoff

potentially harmful chemicals! Unfortunately, the final results of the experiment will not be known for many years.[17] Preliminary results suggest that we should act now, before a hidden time bomb of health problems explodes.

National Water-Quality Assessment Program

The past quarter century has seen significant financial investments and great improvements in manufacturing, processing, and wastewater-treatment facilities, with the objective of reducing the amount of contaminants emitted into our water resources. These programs have significantly improved water quality across the United States; however, considerable apprehension remains concerning the effects of water pollutants, such as nutrients, toxins, and pathogens, on human health and the health of aquatic ecosystems. In response to this need, the U.S. Geological Survey has a program to assess water quality throughout the country. The program integrates both surface-water and groundwater systems that monitor and study aquatic ecosystems. The goals of the program are (1) to carefully describe current water-quality conditions for many of the freshwater streams and aquifers in the United States, (2) to monitor and describe water-quality changes over time, and (3) to increase understanding concerning the human and natural factors that affect the nation's water quality.

One of the largest water systems under study is the Delaware River basin, which includes parts of Pennsylvania, New Jersey, New York, and Delaware (**Figure 14.17**). The drainage basin contains parts of several distinct physiographic provinces, which are regions that share similar topography, rock types, and geologic history. Provinces vary from the relatively flat Coastal Plain and broader uplands of the Piedmont, where 80 percent of the people living in the basin reside, to the more rugged topography of the Valley and Ridge province and the Appalachian Plateaus in the northern portions of the drainage basin. The Delaware River basin includes forested lands (60 percent), agricultural lands (24 percent), urban and residential areas (9 percent), and land taken up by surface water bodies and other miscellaneous land types (7 percent).[18]

Some of the major water-quality issues being addressed in the Delaware River basin study[18] include:

- Effects of the natural river system on the distribution, fate, and effects of contaminants in water, sediment, and living things
- Relationships between the flow of water in the river and concentrations of nutrients, contaminants, and pathogens
- Presence of contaminants, including pathogens and pesticides, in drinking water supplies and in water used for recreational activities
- Development of water-management plans and strategies for the protection of areas of the river basin that have high water quality
- Effects of septic systems, used to treat sewage from individual homes, on water quality and river ecology
- Effects of groundwater withdrawals on water quality
- Effects of discharge from coal mines on water quality and river ecosystems

In addition, the Delaware River basin is being studied with the objective of determining what data are useful for predicting the impacts of climate change.[19] The plan is to monitor the river for changes in response to global warming related to

FIGURE 14.17 River basin studied to monitor and describe water quality Delaware River basin with physiographic provinces. *(After U.S. Geological Survey, 1999.* National Water-Quality Assessment Program, Delaware River Basin. *U.S. Geological Survey Fact Sheet FS-056-99)*

storage of water for New York City, maintaining stream flow requirements for a variety of water uses in the basin, and controlling the migration of saltwater into the Delaware estuary as sea-level rises.[19]

Water Quality and Stream Ecosystems in the United States

Improving the quality of stream ecosystem conditions in the United States is an important goal. Small streams that can be waded are of particular concern because there are so many of them. Nearly every community has several small streams in the immediate area, and local streams are often highly valued by people. Recent studies have aimed to assess small streams in the United States.[20] A standardized field collection of data is an important step. Measurements at a particular stream include:

- Measurement of stream channel morphology and the habitat for living things
- Measurement of the streamside and near-stream vegetation (i.e., *riparian vegetation*)
- Measurement of water chemistry
- Measurement of the near stream biological diversity of plants and animals

Evaluation of collected data includes two key biological indicators: (1) an index of biotic microinvertebrates (insects) living in the stream relative to streams that represent a least-disturbed state and (2) an index that represents a loss of biodiversity. Results of the study are shown in **Figure 14.18**. The top graph is for the entire United States, and the three lower graphs are major regions of the country. The ratings range from poor conditions—that is, those that are most disturbed with respect to environmental stress—to conditions that mostly correspond to undisturbed stream systems. Compared to the western states, streams with poor quality are most numerous in the northeastern part of the United States, as well as in the midsection of the country. Also, the percentage of stream length in good condition is considerably higher in the west than in other parts of the country. This is because the extent of stream channel modifications and changes in land use in the eastern half of the country is large compared to that in the western half. Western states tend to have more mountains and more areas of natural landscape that have not been

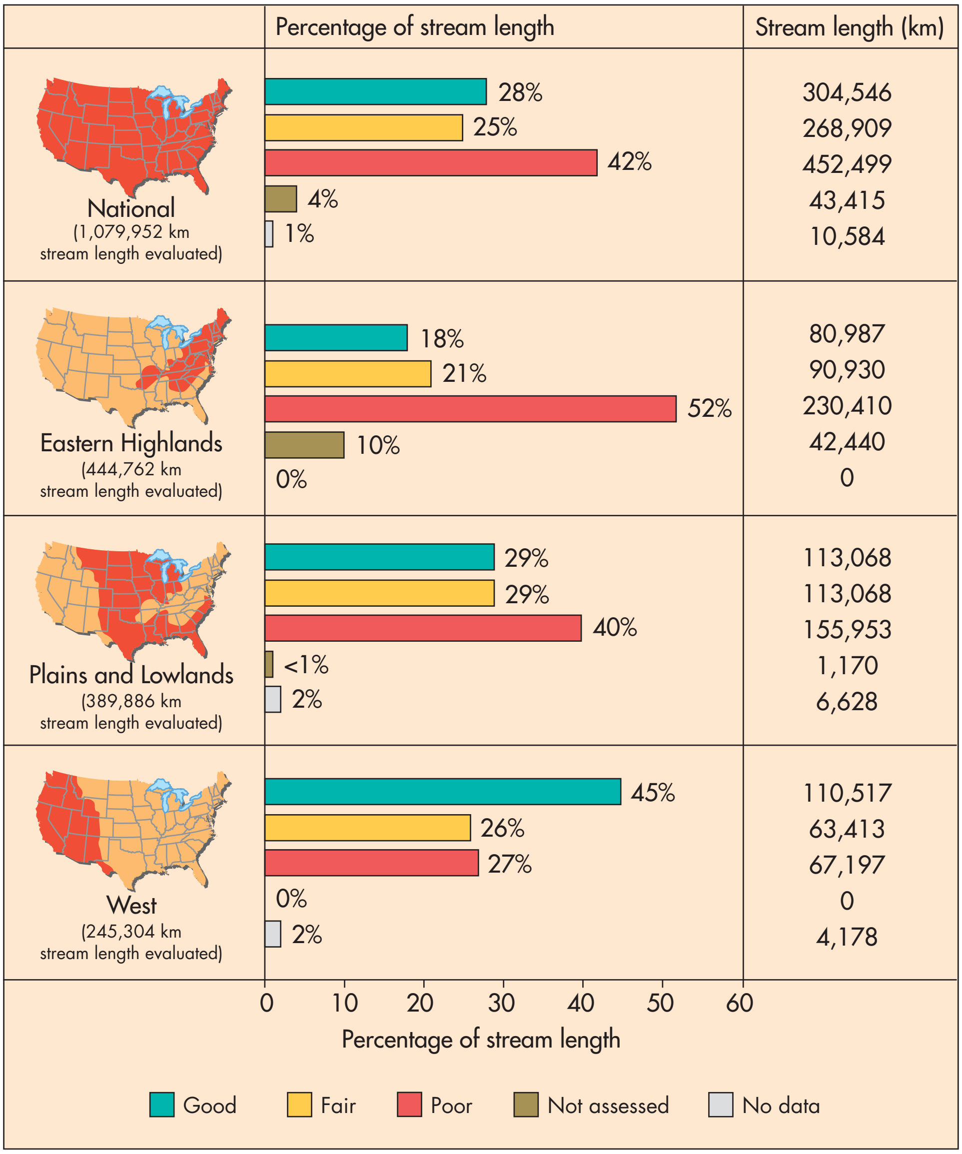


FIGURE 14.18 Health of stream ecosystems Summary of indicators of water and ecosystem quality for small streams that can be waded in the United States. *(After Faustini, J. M., et al. 2009. Assessing stream ecosystem condition in the United States.* EOS, Transactions, American Geophysical Union *90(36):309–310.)*

significantly modified by agriculture and other human activities. On the other hand, streams in the west have a higher risk for future degradation than in other areas because there are more pristine streams against which to measure changes and because there are more high-quality stream ecosystem conditions to potentially be degraded, relative to other parts of the country.[20]

Saltwater Intrusion

Aquifer pollution does not result solely from the disposal of wastes on the land surface or in the ground. Overpumping or mining groundwater allows inferior waters to migrate from both adjacent aquifers and the sea, also causing contamination problems. Hence, human use of public or private water supplies can accidentally result in aquifer pollution. Intrusion of saltwater into freshwater supplies has caused problems in coastal areas of New York, Florida, and California, among other areas.

Figure 14.19 illustrates the general principle of saltwater intrusion. The groundwater table is generally inclined toward the ocean, and a wedge of saltwater is inclined toward the land. Thus, with no confining layers, salty groundwater near the coast may be encountered below the land surface. Because

freshwater is slightly less dense than saltwater, freshwater will float on top of saltwater; the density difference explains why a layer of freshwater can sometimes be found in the ocean offshore from a river's delta. When wells are drilled, a *cone of depression* develops in the freshwater table (Figure 14.19b), which may allow intrusion of saltwater as the interface between freshwater and saltwater rises and forms a *cone of ascension* in response to the loss of freshwater.

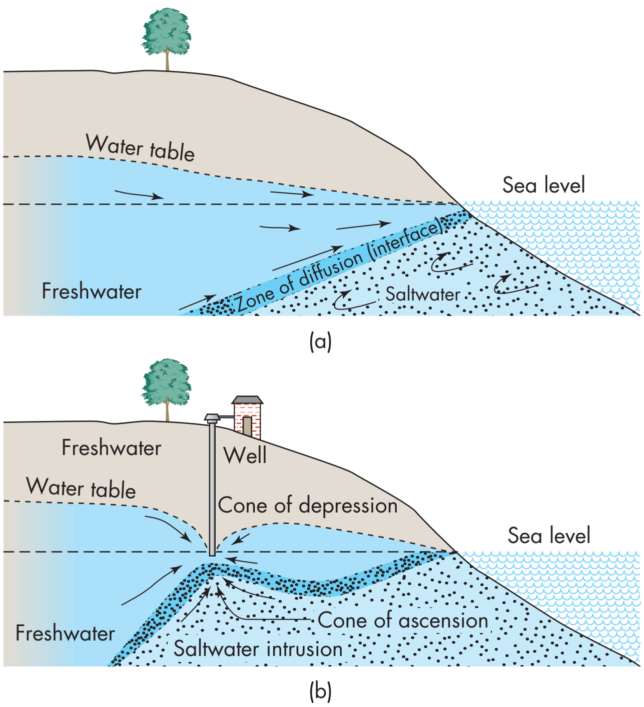


FIGURE 14.19 Saltwater intrusion (a) The groundwater system near the coast under natural conditions. (b) A well with both a cone of depression and a cone of ascension. If pumping is intensive, the cone of ascension may be drawn upward, delivering saltwater to the well.

Groundwater Treatment

The difficulty of detecting groundwater pollution, the long-term residency of groundwater, the degradation of the polluted aquifer, and the difficulty and expense of aquifer recovery establish a strong argument: No wastes or possible pollutants should be allowed to enter any part of the groundwater system. However, preventing the entry of pollutants requires careful protection and management of recharge areas and may, in fact, be impossible. Accidents such as broken pipelines will happen. In order to reduce groundwater pollution, we should learn more about the natural processes that treat wastes, so that when soil and rocks cannot naturally treat, store, or recycle wastes, we can develop processes to make the pollutants treatable, storable, or recyclable. **Table 14.4** briefly outlines some of the methods for treating groundwater. The specific treatment selected depends on variables, such as type of contaminant, method of transport, and characteristics of the local environment, such as depth to the water table and geologic characteristics.

14.5 Water-Quality Standards

A question people commonly ask is, "How safe is our water supply?" Americans believe that they have high-quality drinking water, some of the best in the world. For the most part, we do have high-quality drinking water, but, in recent years, we have gained an ability to detect specific contaminants in parts per billion (ppb) or, in some cases, even parts per trillion (ppt) of water. The question that then arises is, "How dangerous might some of these chemicals be?" You may think that very small amounts of contaminants cannot possibly be dangerous, but, as the

TABLE 14.4 Methods of Treating Groundwater and Vadose-Zone Water

Extraction Wells	Vapor Extraction	Bioremediation	Permeable Treatment Bed
Pumping out contaminated water and treatment by filtration, oxidation, air stripping (volatilization of contaminant in an air column), or biological processes	Use of vapor-extraction well and then treatment	Injection of nutrients and oxygen to encourage growth of organisms that degrade the contaminant in the groundwater	Use of contact treatment as contaminated water plume moves through a treatment bed in the path of groundwater movement; neutralization of the contaminant by chemical, physical, or biological processes

U.S. Environmental Protection Agency (EPA) reminds us, a small number of viruses (non-living microscopic particles that attack healthy cells) can cause a disease. Physicians are able to delineate what diseases are caused by particular viruses, but we are less sure about the effects of long-term exposure to very small amounts of chemicals.

In response to this concern, the U.S. Congress has mandated that the EPA establish minimum national drinking water standards for a variety of chemicals and other materials. In 1986, Congress expanded the Safe Drinking Water Act of 1974 to include 83 contaminants. Among other regulations, the new legislation banned the use of lead in the installation or repair of water systems used for drinking water. Health effects associated with lead toxicity are very well known. At high concentrations, lead causes damage to the nervous system and the kidneys and is particularly toxic to infants and pregnant women.[21]

The EPA has set standards for a number of contaminants that might be found in our drinking water. However, only two substances for which these standards have been set are thought to pose an immediate health threat when standards are exceeded:[21]

- Coliform bacteria, possibly indicating that the water is contaminated by harmful disease-causing organisms
- Nitrate, because contamination above the standard is an immediate threat to young children. In some children younger than 1 year old, high levels of nitrate may react with their blood to produce an anemic condition known as "blue baby."

Table 14.5 is an abbreviated list illustrating some of the contaminants included in the EPA's list of National Primary Drinking Water Standards and related health problems. The purposes of the standards and regulations concerning drinking water are:[21]

- To ensure that our water supply is treated to remove harmful contaminants
- To regularly test and monitor the quality of our water supply
- To provide information to citizens so that they are better informed concerning the quality and testing of their water supply

14.6 Wastewater Treatment

Water that is used for municipal and industrial purposes is often degraded by a variety of contaminants, including oxygen-demanding materials, bacteria, nutrients, salts, suspended solids, and other chemicals. In the United States, laws dictate that these contaminated waters must be treated before they are released back into the environment. Wastewater treatment in the United States is big business, costing several tens of billions of dollars per year. In rural areas, the conventional method of treatment uses septic-tank disposal systems. In larger communities, wastewater is generally collected and centralized in water-treatment plants that collect the wastewater from a sewer system.

In many parts of the country, water resources are being stressed. As a result, innovative systems are being developed to reclaim wastewater so that it can be used for such purposes as irrigating fields, parks, or golf courses rather than being discharged into the nearest body of water. New technologies are also being developed to convert wastewater into a resource that can be used. Those developing the new technologies say that sewage-treatment sites should not have to be hidden from people's eyes and noses. Rather, we should come to expect sewage to be reclaimed at a small cost while producing flowers and shrubs in a more gardenlike setting.[22]

Septic-Tank Sewage Disposal

In the United States, the population continues to move from rural to urban, or urbanizing, areas. Although using municipal sewers and using sewage-treatment facilities are the most effective method of sewage disposal, construction of an adequate sewage system has often not kept pace with growth. As a result, the individual septic-tank disposal system continues to be an important method of sewage disposal. There are more than 26 million septic-tank systems in operation, and about half a million new systems are added each year. As a result, septic systems are used by about 20 percent of homes in the United States. Not all land, however, is suitable for installation of a septic-tank disposal system, so evaluation of individual sites is necessary and often required by law before a permit can be issued.

TABLE 14.5 National Drinking Water Standards: Some Examples

Contaminant	Maximum Contaminant Level (mg/L)	Comments/Problems
Inorganics		
Arsenic	0.05	Highly toxic
Cadmium	0.01	Kidney
Lead	0.015[1]	Highly toxic
Mercury	0.002	Kidney, nervous system
Selenium	0.01	Nervous system
Asbestos	7 MFL[2]	Causes benign tumors
Fluoride	4	Leads to skeletal damage
Organic chemicals		
Pesticides		
Endrin	0.0002	Nervous system, kidney
Lindane	0.004	Nervous system, kidney, liver
Methoxychlor	0.1	Nervous system, kidney, liver
Herbicides		
2,4D	0.07	Liver, kidney, nervous system
Silvex	0.05	Nervous system, liver, kidney
Volatile organic chemicals		
Benzene	0.005	Cancer
Carbon tetrachloride	0.005	Possible cancer
Trichloroethylene	0.005	Probable cancer
Vinyl chloride	0.002	Cancer risk
Microbiological organisms		
Fecal coliform bacteria	1 cell/100 mL	Indicator—disease-causing organisms

[1]The action level for lead related to treatment of water to reduce lead to the safe level. There is no maximum contaminant level for lead.
[2]MFL = million fibers per liter with fiber length > 10 micrometers.
U.S. Environmental Protection Agency.

The basic parts of a **septic tank** are shown in Figure 14.20. The sewer line from the house or small business leads to an underground septic tank in the yard. Solid organic matter settles to the bottom of the tank, where it is digested and liquefied by bacterial action. This is part of the treatment that reduces solid organic material to a more liquid state. The liquid wastewater discharges into either a drain field, also called an absorption field, which is a system of shallowly buried perforated piping, or a large-diameter, deep, gravel-filled "dry well" through which the wastewater seeps into the surrounding soil. As the wastewater moves through the soil, it is further treated and purified by natural processes of filtering and oxidation.

Geologic factors that affect the suitability of a septic-tank disposal system in a particular location include type of soil, depth to water table, depth to bedrock, and topography. These variables are generally included in the soil descriptions found in the soil survey of an area. Soil surveys are published by the Soil Conservation Service and are extremely valuable when evaluating potential land use, such as suitability for a septic system. However, the reliability of a soils map for predicting the limitations of soils is confined to an area smaller than a few

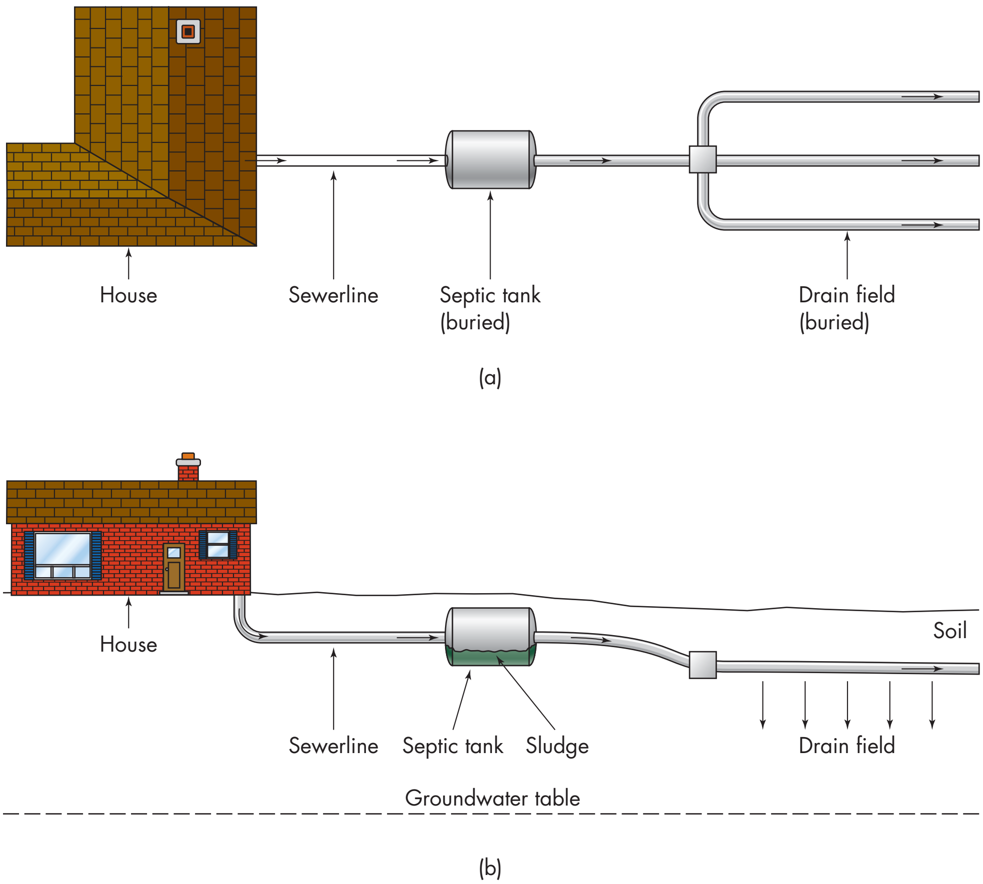


FIGURE 14.20 Septic tank Sewage disposal system for a home. (a) Plan (map) view. (b) Cross section.

thousand square meters, and soil types can change within a few meters, so it is often necessary to have an onsite evaluation by a soil scientist or soils engineer. To calculate the size of the drain field needed, one must know the rate at which water infiltrates into the soil, which is best determined by testing the soil.

Sewage drain fields may fail for several reasons. The most common cause is poor soil drainage, which allows the wastewater to rise to the surface in wet weather. Poor drainage can be expected to be present in areas with clay-rich soils or rock, such as shale, with low hydraulic conductivity (Chapter 13), in areas with a water table that is near the surface, or in areas of frequent flooding.

When septic systems fail, waste materials often surface above the drain field, producing a potential health hazard. This sort of failure is easy to see. Unfortunately, what is happening beneath the ground is not so easy to see, and if extensive leaching of waste occurs at the water table, groundwater resources may be polluted. Septic systems that serve small commercial and industrial activities are of particular concern. They tend to cause severe problems of groundwater pollution because of the potentially hazardous nature of the waste being disposed. Possible contaminants include nutrients, such as nitrates; heavy metals, such as zinc, copper, and lead; and synthetic organic chemicals, such as benzine, carbon tetrachloride, and vinyl chloride. In recent years, the EPA has identified a number of commercial and industrial septic systems that caused substantial water pollution that necessitated cleanup.[23]

Wastewater-Treatment Plants

The main purposes of wastewater treatment for municipal sewage from homes and industry are to break down and reduce the amount of organic solids and BOD and to kill bacteria in the wastewater. In addition, new techniques are being developed to remove nutrients and harmful dissolved inorganic materials that may be present.

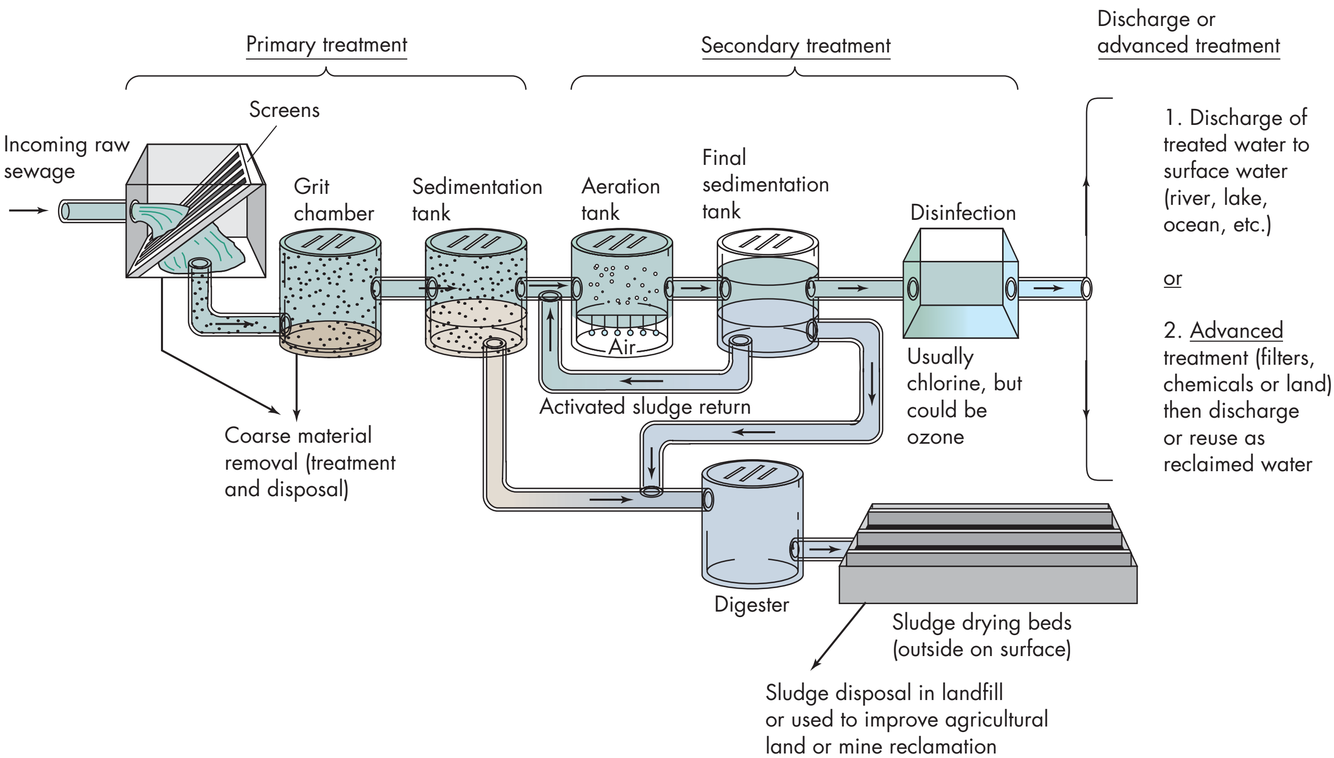


FIGURE 14.21 Sewage treatment Idealized diagram showing activated sludge sewage treatment with or without advanced treatment.

Existing wastewater treatment generally has two or three stages (**Figure 14.21**):

- ***Primary treatment.*** The *primary treatment* stage includes screening, which removes the grit composed of sand, stones, and other large particles; and sedimentation, in which much of the remaining particulate matter (mostly organic) settles out to form a mud-like sediment called *sludge*. The sludge is piped to the digester, and the partially clarified wastewater goes on to the secondary stage of treatment. Primary treatment removes 30 to 40 percent of the pollutants from the wastewater.[24]
- ***Secondary treatment.*** Although there are several methods, the most common *secondary treatment* is known as *activated sludge*. Wastewater from primary treatment enters the aeration tank, where air is pumped in and aerobic, or oxygen-requiring, bacteria break down much of the organic matter remaining in the waste. The wastewater is then pumped to the final sedimentation tank, where sludge settles out and is pumped to the digester. Some of the sludge, rich in bacteria, is recycled back to the aeration tank as "activated sludge" to act as a starter. Thus, the bacteria are used over and over again. The digester provides an oxygen-poor environment in which anaerobic bacteria, those that do not require oxygen, can break down organic matter in the sludge from both the primary and secondary sedimentation tanks. This anaerobic digestion produces methane gas, a by-product that can be used as a fuel to help heat or cool the plant or to run equipment. After secondary treatment, about 90 percent of the organic material (BOD) in the waste has been removed. However, this treatment does not remove nitrogen, phosphorus, heavy metals, or some human-made chemicals, such as solvents and pesticides.[24] The final part of secondary treatment is disinfection of the wastewater. This is usually done with chlorine, but sometimes ozone is used. The treated wastewater is usually discharged to surface waters (rivers, lakes, or the ocean, where water quality problems can still occur; see A Closer Look: Boston Harbor: Cleaning Up a National Treasure), but in some places it is discharged to disposal wells, as for example, in Maui, Hawaii.

A Closer Look

Boston Harbor: Cleaning Up a National Treasure

The city of Boston is steeped in early American history. The names Samuel Adams and Paul Revere immediately come to mind in relation to this period in the late 1700s when the colonies were struggling to obtain freedom from Britain. In 1773, Samuel Adams led a group of patriots aboard three British ships, dumping their cargo of tea into Boston Harbor. The issue that the patriots were emphasizing was what they believed to be an unfair tax on tea, and the event became known as the "Boston Tea Party." The tea dumped into the harbor by patriots in the Boston Tea Party did not pollute the harbor, but the growing city and dumping of all sorts of waste eventually did. For about 300 years, Boston harbor has been a disposal site for dumping of sewage, treated wastewater, and water contaminated from sewer overflows during storms. Late in the twentieth century, court orders demanded that measures be taken to clean up the bay.

After studying Boston Harbor and further offshore in Massachusetts Bay, it was decided to relocate the areas of discharge of waste (called *outfalls*) further offshore from Boston Harbor (**Figure 14.B**). Pollution of the harbor resulted because the waste that was being placed there moved into a small, shallow part of Massachusetts Bay. Although there is vigorous tidal action between the harbor and the bay, the flushing time is about 1 week. The input of wastewater from the sewage outfalls was sufficient to cause water pollution. Study of Massachusetts Bay suggested that the outfalls, if placed further offshore where water is deeper and currents are stronger, would lower the pollution levels in Boston Harbor.[25]

Moving the wastewater outfall offshore was definitely a step in the right direction, but the long-term solution to pollutants entering the marine ecosystem will require additional measures. Pollutants in the water, even when placed further offshore with greater circulation and greater water depth, will eventually accumulate and cause environmental damage. As a result, any long-term solution must include source reduction of pollutants. To this end, the Boston Regional Sewage Treatment Plan called for a new treatment plant

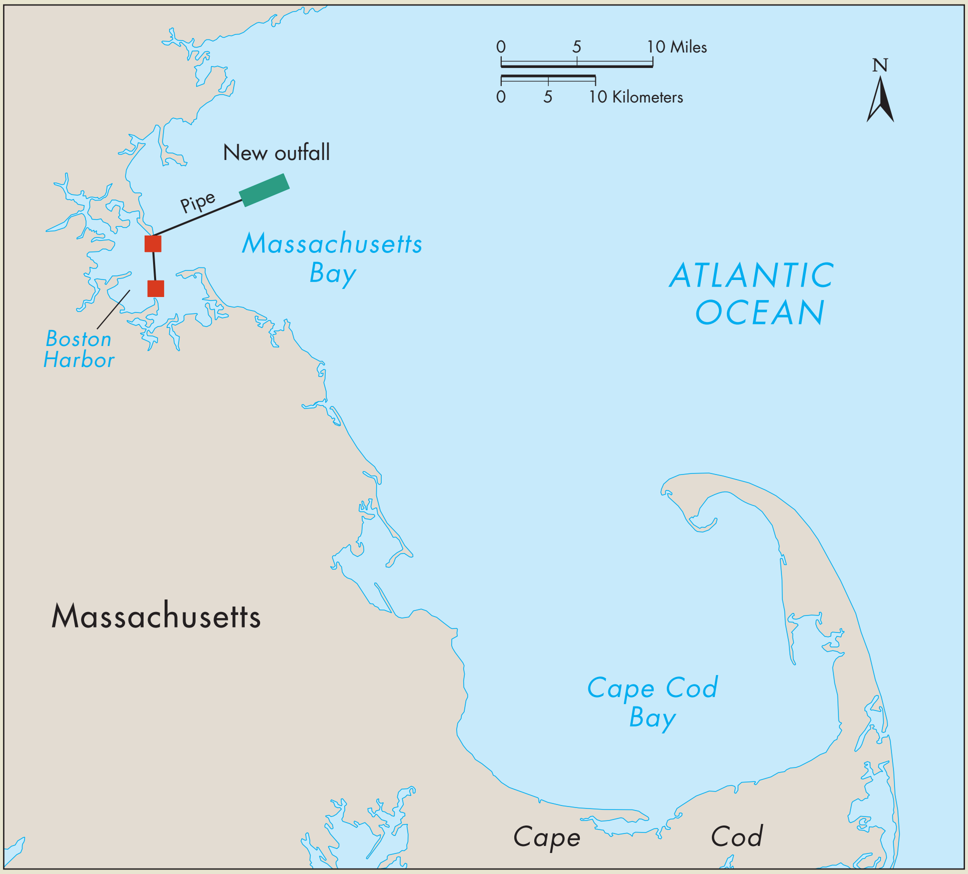


FIGURE 14.B Boston Harbor and Massachusetts Bay Diagram shows old sewage outfalls (red squares) and new outfall (green rectangle) 15 km offshore. *(Modified after U.S. Geological Survey Fact Sheet FS-185-97, 1997)*

designed to significantly reduce the levels of pollutants that are discharged into the bay. This acknowledges that dilution by itself cannot solve the urban waste management problem. Today the $3.8 billion Deer Island Sewage Treatment Plant collects and treats sewage from 43 greater Boston communities. Moving the sewage outfall offshore when combined with source reduction of pollutants is a positive example of what can be done to better manage our waste and reduce environmental problems.[25]

- ***Advanced treatment.*** Used to remove nutrients, heavy metals, or specific chemicals, the *advanced treatment* stage may be required if higher-quality treated wastewater is needed for particular uses, such as for wildlife habitat or irrigation of golf courses, parks, or crops. The treated wastewater for such uses is often referred to as **reclaimed water**. Methods of advanced treatment include use of chemicals, sand filters, or carbon filters. After advanced treatment, up to 95 percent of the pollutants in the wastewater have been removed.

A troublesome aspect of wastewater treatment is the handling and disposal of sludge. Sludge generated from industrial wastewater may contain heavy metals, as well as other toxic materials, and is a hazardous waste. Many communities now require industry to pretreat their sewage to remove heavy metals before it is sent to a municipal treatment plant.

The amount of sludge produced in the treatment process is conservatively estimated at about 54 to 112 g per person per day, and sludge disposal accounts for 25 to 50 percent of the capital and operating cost of a treatment plant.

Sludge handling and disposal have four main objectives:[26]

- To convert the organic matter to a relatively stable form
- To reduce the volume of sludge by removing liquid
- To destroy or control harmful organisms
- To produce by-products, the use or sale of which reduces the cost of processing and disposal of the sludge

Final disposal of sludge is accomplished by incineration, burial in a landfill, use for soil reclamation, or ocean dumping. From an environmental standpoint, the best use of sludge is to improve soil texture and fertility in areas disturbed by activity, such as strip mining and poor soil conservation. Although it is unlikely that all the tremendous quantities of sludge generated by large metropolitan areas can ever be used for beneficial purposes, many industries, institutions, and agricultural activities can take advantage of municipal and animal wastes by converting them into resources.

Wetlands as Wastewater-Treatment Sites

Natural and human-constructed wetlands are potentially good places to treat or partially treat wastewater or other poor-quality water. Wetland treatment is attractive to communities that have difficulty purchasing expensive traditional wastewater-treatment plants or desire an alternative to the traditional plants. The states of Louisiana and Arizona, which have very different climates—warm-humid and hot-dry, respectively—have both had success using wetlands to treat wastewater.

Advanced treatment of wastewater in Louisiana, by applying nitrogen- and phosphorus-rich wastewater to coastal wetlands, is improving water quality as the wetland plants use these nutrients in their life cycle. In Louisiana, use of coastal wetlands to remove nutrients has resulted in considerable economic savings over use of conventional advanced wastewater treatment.[27]

Near Phoenix, Arizona, human-constructed wetlands are used to treat poor-quality agricultural wastewater with high nitrogen concentration. The artificial wetland is within a residential community and consists of ponds with wetland plants and bacteria that reduce the nitrogen to acceptable levels before discharging the water to a nearby river channel, where it seeps into the ground to become a groundwater resource.

Wastewater Renovation

The process of recycling treated liquid waste is called the **wastewater renovation and conservation cycle**. The primary processes in the cycle are the return of treated wastewater by artificial groundwater recharge at specially designed basins (i.e., ponds), dry river beds, or other land, such as a forest; renovation by natural purification of wastewater as it slowly seeps through soil, sediment, and rock to eventually recharge the groundwater resource with clean water; and reuse, or *conservation*, of the water by pumping it out of the ground for municipal, industrial, institutional, or agricultural purposes.[28] Of course, not all aspects of the cycle are equally applicable to a particular wastewater problem.

Wastewater renovation from cattle feedlots differs considerably from renovation of water from industrial or municipal sites. However, the general principle of renovation is valid, and the processes are similar in theory.

The return and renovation processes are crucial to wastewater recycling, and soil and rock type, topography, climate, and vegetation play significant roles. In the planning of return and renovation processes, it is particularly important that the soil be able to safely assimilate treated wastewater, that the selected vegetation can use the nutrients in the wastewater, and that the volume of wastewater that can safely be applied to the area is known.[29]

In Clayton County, Georgia, just south of Atlanta, a large 1,460 ha (3,600 acre) land application water renovation and conservation cycle project was initiated in 1982. The project applies treated wastewater to a pine forest by irrigation. The trees remove nitrogen from the wastewater as part of their life cycle. Trees are harvested on a 20-year rotation. The forest is part of the watershed that supplies water to the area; therefore, wastewater is recycled to become part of the drinking-water supply.[30]

Atlantis, South Africa, has for several decades developed a plan that augments their water supply by about 30 percent through artificial recharge. The population of Atlantis is about 60,000 people, and the community is almost entirely dependent upon groundwater resources. This results because the climate is semiarid, and the surficial deposits soak up much of the precipitation, which limits natural runoff. Faced with eventual water shortages, the community developed an innovative groundwater recharge scheme. As the community was being developed, it separated the water supply into two components: One component is for the municipal supply for domestic water use of homes, and the second is the water supply for the industrial activities. Because these two water sources are separated, they go to different water treatment plants. From these plants, the water is taken to recharge basins, where it infiltrates into the subsurface. The infiltration of the industrial wastewater near the coast produces a recharge mound in the water table that helps protect the water supply from saltwater intrusion. Artificial recharge basins further inland accept stormwater runoff and treated wastewater. The water infiltrates to become part of the groundwater system, where it is renovated (i.e., purified) by natural processes. The water is then pumped from wells and used by the community as part of the water supply. The basics of this system are shown in **Figure 14.22**. The innovative part of the water renovation scheme for Atlantis is the separation of the two water sources and subsequent separate treatment and artificial recharge for different purposes.[31]

Southern California, with its semiarid climate, needs to import much of its water supply. As a result, water shortages are always a potential threat. Development in Orange County, California, in recent decades, has been rapid and extensive. Artificial recharge to augment groundwater resources in northern Orange County has been an ongoing project for a number of years. About 200,000 acre-feet (2.5×10^8 m^3) of water is recharged annually. Some of this water, in recent years, has included wastewater. The purpose of the artificial recharge is to increase the water supply as a result of annual increase in water demands and also to improve water quality by utilizing the natural purification processes of water as it moves through the subsurface environment. This combination reduces public health risk from potential exposure to contaminated water or pathogens. In Orange County, the water district applies advanced treatment technologies to wastewater prior to injecting it into the subsurface through artificial recharge. The district has built a 70-million gallons per day advanced water recycling plant where the water from the plant is recharged through a spreading facility. The water can then be pumped out and reused.[32]

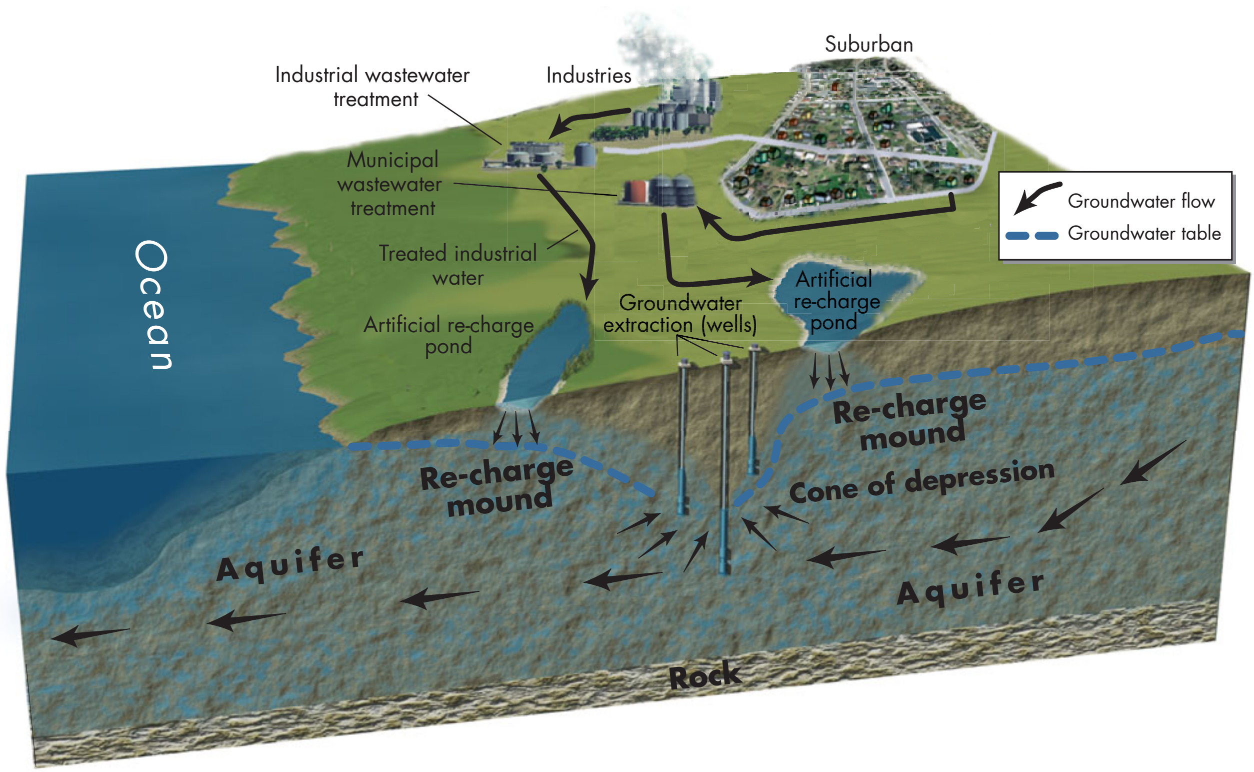


FIGURE 14.22 The wastewater renovation and conservation cycle Idealized diagram of the wastewater renovation and conservation cycle used in Atlantis, South Africa. Wastewater from industrial sources and homes is separated and sent to different basins, where it seeps into the ground to replenish the groundwater in a process called *artificial recharge*. The water is renovated (i.e., cleaned) as it moves through the soil and rock. Some of the water is used as a barrier to inhibit saltwater intrusion, and inland wells draw the renovated water to be reused.

14.7 Federal Legislation

In the United States, the mid-1990s saw much debate and controversy regarding water pollution. Republicans, then in control of the House of Representatives and the Senate, attempted to rewrite major environmental laws, including the Clean Water Act of 1972 (amended in 1977). Their purpose was to give industry greater flexibility in choosing how to comply with environmental regulations concerning water pollution. Industry is in favor of proposed new regulations that, in their estimation, would be more cost-effective without causing an increase in environmental degradation. Environmentalists viewed the attempts to rewrite the Clean Water Act as a step backward in the nation's decades-long fight to clean up its water resources. Apparently, the Republican majority misinterpreted the public's position on this issue. Survey after survey established that there is strong support for a clean environment in the United States today. People are willing to pay to have clean air and clean water for this and future generations. There was a strong backlash and criticism of steps taken to weaken environmental laws, particularly as they pertain to important resources, such as water. Thus, the debate went on. The Water Quality Act of 1987 established national policy to control nonpoint sources of water pollution, but it did not go far enough in protecting water resources.[33]

In July 2000, President Clinton, in defiance of Congress, imposed new water pollution controls to protect thousands of streams and lakes from nonpoint sources of agricultural, industrial, and urban pollution. The rules are administered by the Environmental Protection Agency, which works with states and local communities to develop detailed programs with the objective of reducing pollution to those streams, rivers, lakes, and estuaries that do not now meet the minimum standards of water quality. The rules imposed demonstrate that

nonpoint sources of water pollution are recognized as a serious problem that is difficult to regulate. The plan will take at least 15 years to implement completely. It has been opposed for years by Congress, as well as by some agricultural groups, the utility industry, and even the U.S. Chamber of Commerce. In 2001, the newly elected President Bush temporarily suspended some regulations, including control of arsenic in water, over the objections of many who were concerned that some people were drinking contaminated water. The primary objections of those who oppose controls are that (1) the requirements would be costly (billions of dollars) and (2) local and state governments are better suited to implement water pollution rules. Nevertheless, the regulations are now in place and are another step in water pollution control measures started many years ago in the United States.

14.8 What Can Be Done to Reduce Effects of Water Pollution?

This chapter has documented a long list of water pollutants, ranging from disease-causing organisms to chemical pollutants. We now turn to what is needed to better address water pollution problems. Several suggestions follow:[4]

- Develop and refine better ways to evaluate water pollution problems and their impact on aquatic life and the health of people.
- Implement cost-effective new and innovative water treatment technologies.
- Develop products and processes that minimize production of water pollutants and their release into the environment.

Making The Connection

Linking the Opening Case History About Pig Farms in North Carolina to the Fundamental Concepts

Consider and discuss the following questions:

1. What are the impacts of population increase on the pig-farming industry, and does that have any bearing on the pig-waste problem? What other factors are important?
2. Is sustainable water management possible on the Piedmont of North Carolina if pig farms continue conducting business as usual? If you think it is not sustainable, what needs to be done?
3. How do science and values link to future planning to manage industrial-level raising of pigs?

Summary

Water pollution is the degradation of water quality, as measured by physical, chemical, or biological criteria. These criteria take into consideration the intended use for the water, departure from the norm, effects on public health, and ecological impacts. The most serious water pollution problem today is the lack of noncontaminated drinking water for billions of people.

Surface-water pollutants have point or nonpoint sources. The major water pollutants are oxygen-demanding waste, measured by biochemical oxygen demand (BOD); pathogens, measured by the fecal coliform bacteria count; nutrients that lead to eutrophication, in which overgrowth of algae deprives water of oxygen and sunlight; oil; toxic substances, including synthetic organic and inorganic compounds, heavy metals, and radioactive materials; heat; and sediment. Acid mine drainage refers to water with a high concentration of sulfuric acid that drains from some coal or metal mining

areas, causing surface water and groundwater pollution.

Development of water-quality standards in the United States has been mandated by federal legislation and involves setting of maximum contaminant levels for contaminants that might be found in our drinking water. The major purposes of the standards are to ensure that our water supply is treated to remove harmful contaminants and that water quality is regularly tested and monitored.

Wastewater-treatment facilities include septic-tank sewage disposal systems and wastewater-treatment plants. Septic-tank systems, used by homes and small commercial and industrial activities, are very common in the United States today. Failure of these systems may cause significant pollution to groundwater resources. Wastewater treatment plants collect and process water from municipal sewage systems. The use of reclaimed water is growing fast in the United States today, particularly in areas where water shortages are most likely to occur.

Revisiting Fundamental Concepts

Human Population Growth As human population has grown, particularly in large urban regions, groundwater and surface water are often polluted. Pollution reduces the water resources available and makes it necessary in some urban areas to import water, sometimes from far away. As human population continues to increase during the next decades, we will need to find creative ways to avoid continual pollution of water resources that we depend on. Groundwater is particularly vulnerable and difficult to treat once polluted.

Sustainability At the very heart of sustainability is the desire to pass on a quality environment to future generations. Certainly, a quality environment includes the water we drink and use to grow our crops. It is apparent that our present management practices to maintain high water quality are not sustainable. That is, if we continue present practices, more and more of our water resources will become contaminated and polluted, becoming unfit for human use. Therefore, it is of the utmost importance to find ways to use water resources responsibly, in a sustainable way. Recent regulations and laws to restrict water pollutants are steps in the right direction.

Earth as a System Our water resources are part of complex hydrologic, physical, chemical, and biological systems that are prone to change and disturbance. When we introduce pollutants into our surface-water or groundwater resources, we cause further changes to ecosystems that support people and other living things. We have learned that we cannot do just one thing. For example, when we introduce toxic materials, such as MTBE, into the groundwater, we cause far-reaching changes to the environment. These changes often cause further changes.

Hazardous Earth Processes, Risk Assessment, and Perception The largest and most significant water pollution hazard is the lack of noncontaminated water for billions of people on Earth. Epidemics caused by poor water quality and pathogenic organisms have been nearly eliminated in developed countries, but they are still serious problems in parts of the world where people do not have the financial ability to treat water before it is consumed. We have the perception in the United States that our water supply is clean and free of disease-causing agents. From time to time, though, we learn differently, and, although outbreaks of disease have been isolated, there is concern for our future supply of clean drinking water.

Scientific Knowledge and Values The role of particular toxins and pollutants in our water resources is a science still in its infancy. In particular, we have trouble making decisions concerning what the toxic level of a particular chemical is and what the effects are likely to be in the future. How we decide to deal with living with this uncertainty is in part a function of our value system. We may choose to be conservative and restrict the use of potentially toxic chemicals, or we may assume that our present practices will not cause problems for future generations. We have learned in the past that making the assumption that problems will not result from a particular practice has been costly. For example, a decision was recently made not to control arsenic in groundwater used by people in parts of California and other areas. This decision was made despite the fact that arsenic is known to be very toxic. Part of the reason for choosing not to restrict the level of arsenic in drinking water was that treatment of the water to remove the arsenic would be overly costly to society. The decision not to remove the arsenic constitutes an experiment on how the arsenic in the environment will affect people and ecosystems.

Key Terms

acid mine drainage (p. 483)
biochemical oxygen demand (BOD) (p. 469)
cultural eutrophication (p. 472)
nonpoint source (p. 481)
point source (p. 480)
pollutant (p. 468)
pollution (p. 480)
reclaimed water (p. 494)
septic tank (p. 490)
wastewater renovation and conservation cycle (p. 495)
water pollution (p. 468)

Review Questions

1. Define *water pollution*.
2. Define *biochemical oxygen demand*.
3. What is the role of fecal coliform bacteria in determining water pollution?
4. Define *cultural eutrophication*.
5. Differentiate between point sources and nonpoint sources of water pollution.
6. What is acid mine drainage?
7. What is saltwater intrusion?
8. Differentiate among primary, secondary, and advanced wastewater treatment.
9. What are some of the ways that a septic-tank disposal system may fail?
10. Describe the wastewater renovation and conservation cycle.

Critical Thinking Questions

1. For your community, develop an inventory of point sources and nonpoint sources of water pollution. Carefully consider how each of them might be eliminated or minimized as part of a pollution-abatement strategy.
2. Visit a wastewater-treatment plant. What processes are used at the plant? Could the concept of resource recovery or wastewater renovation and conservation be used? What would be the advantages and disadvantages of using a biological system, such as plants, as part of the wastewater-treatment procedures?
3. How safe do you think your water supply is? Upon what are you basing your answer? What do you need to know to give an informed answer?

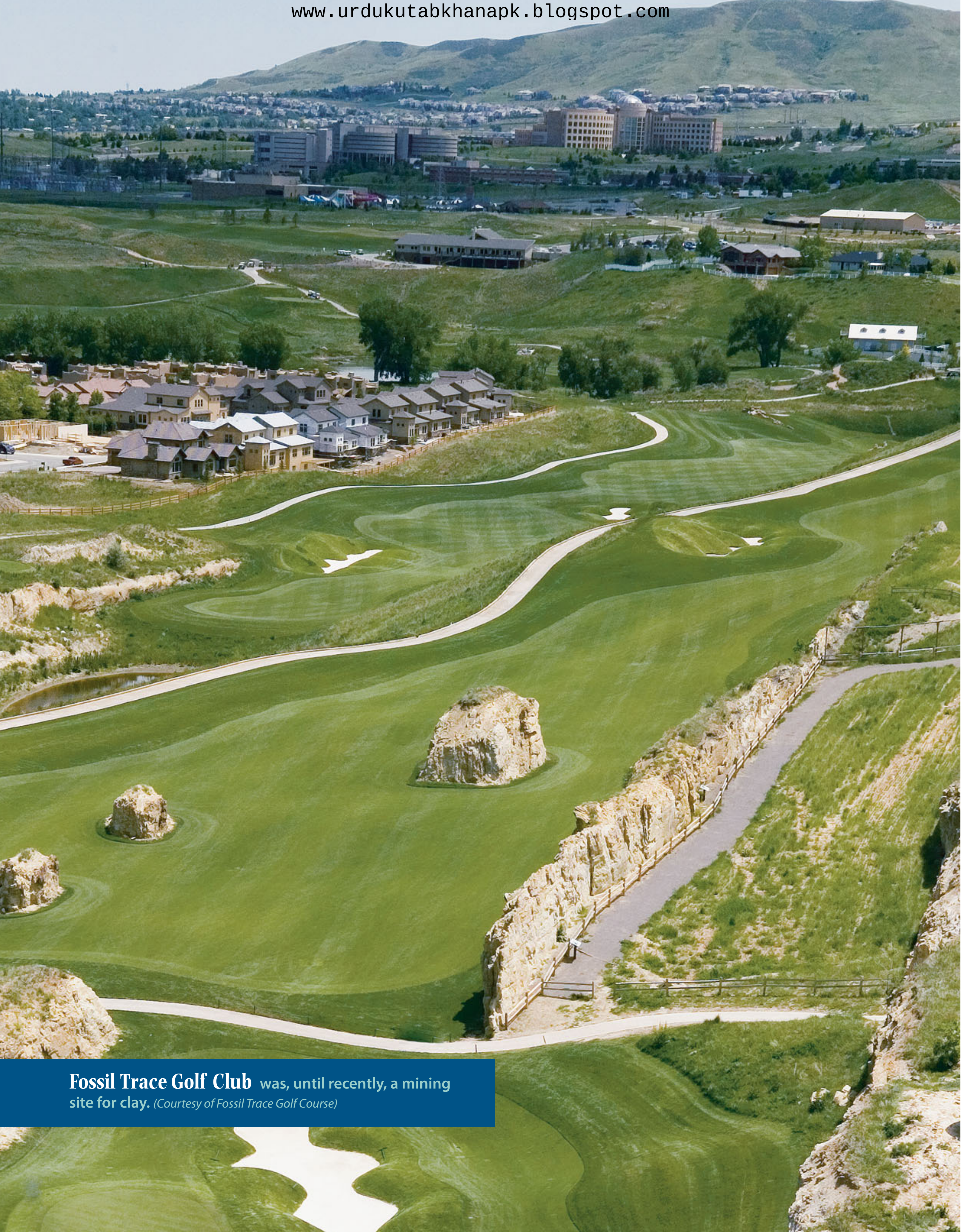
Companion Website

www.mygeoscienceplace.com

PEARSON mygeoscience place™

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.



Fossil Trace Golf Club was, until recently, a mining site for clay. *(Courtesy of Fossil Trace Golf Course)*

15 Mineral Resources and the Environment

Learning Objectives

Our modern society completely depends on the availability of mineral resources. As world population increases, we face an ever-increasing resource crisis. It is feared that Earth may have reached its capacity to absorb environmental degradation related to mineral extraction, processing, and use. In this chapter, we will focus on the following learning objectives:

- **Understand the relationship between human population and resource utilization**
- **Understand why minerals are so important to modern society**
- **Understand the difference between a resource and a reserve and why that difference is important**
- **Know some of the factors that control the availability of mineral resources**
- **Understand the environmental impact of mineral development**
- **Know the potential benefits that biotechnology can offer to environmental cleanup associated with mineral extraction and production**
- **Understand the economic and environmental role of recycling mineral resources**
- **Understand the relationship between sustainability and mineral use**

Case History

Mine Near Golden, Colorado, Is Transformed into a Golf Course

An award-winning golf course is now located on land that was, for about 100 years, an open-pit mine (quarry) in limestone rock near the city of Golden, Colorado. The mine produced clay from layers between the limestone beds to make bricks. The bricks were used as a building material for buildings in the Denver area, including the Colorado governor's mansion. The mining site included unsightly pits with vertical limestone walls, as well as a landfill for waste disposal. The area has spectacular views of the foothills and the Rocky Mountains. Today, the limestone cliffs left by the mining, with their exposed plant and dinosaur fossils, have been transformed into golf greens and fairways. The name of the golf course is Fossil Trace, reflecting its geologic heritage. Trails lead to the best locations to see fossils—an added incentive to visit the area. Constructed wetlands and three lakes store runoff of floodwater, helping protect Golden from flash floods. The reclamation project started with the desire for a public golf course. The mine reclamation demonstrates that previous mines can be reclaimed and transformed into valuable property.

Fossil Trace Golf Club is a unique instance of mine reclamation. However, each potential site for restoration offers opportunities based on local physical, hydrological, and biological conditions. This chapter discusses the origin of mineral deposits, environmental consequences of mineral development, and sustainable mineral use.

15.1 Minerals and Human Use

Our society depends on the availability of mineral resources.[1] Specifically, consider your breakfast this morning. You probably drank from a glass made primarily of quartz-sand; ate food from dishes made from clay; flavored your food with salt mined from Earth; ate fruit grown with the aid of fertilizers, such as potassium carbonate (potash) and phosphorus; and used utensils made from stainless steel, which comes from processing iron ore and other minerals. If you read a magazine or newspaper while eating, the paper was probably made using clay fillers. If the phone rang and you answered, you were using more than 40 minerals in the telephone. You may have listened to music on your iPod while eating or made your day's appointments with your BlackBerry. These electronic items are made of metals and petroleum products. When you went to school or work, you may have turned on a computer or other equipment made largely of minerals (**Figure 15.1**).[1–3]

Minerals are extremely important to people; all other things being equal, one's standard of living increases with the increased availability of minerals in useful forms. Furthermore, the availability of mineral resources is one measure of the wealth of a society. Societies that have been successful in the location, extraction, or importation and use of minerals have grown and prospered. Without mineral resources, modern technological civilization as we know it would not be possible.

Minerals are an important part of the U.S. economy. Selected aspects of the role of nonfuel minerals in the 2009 U.S. economy are:[4]

- The value of domestic minerals produced from mining was about \$57.1 billion.
- Domestic processed materials from minerals had a value of \$454 billion, which is about 3 percent of the U.S. gross domestic product (GDP) (\$14,200 billion in 2009).
- The value of domestic reclaimed metals and mineral products at \$9.3 billion was about 16 percent of the value of domestic minerals produced from mining—a significant contribution.
- The value added by major industries such as construction and manufacturing of durable goods (those goods not consumed immediately but that wear out over time) that use processed mineral materials was \$1,900 billion, which is about 13 percent of the GDP.

1. Computer—Includes gold, silica, nickel, aluminum, zinc, iron, petroleum, products and about thirty other minerals.
2. Pencil—Includes gaphite and clays
3. Telephone—Includes copper, gold, and petroleum products.
4. Books—Includes limestone and clays.
5. Pens—Includes limestone, mica, petroleum products, clays, silica, and talc.
6. Blackberry—Includes gold, nickel, silica, zinc, and petroleum products.
7. Camera—Includes silica, zinc, copper, aluminum, and petroleum products.
8. Chair—Includes aluminum and petroleum products.
9. Television—Includes aluminum, copper, iron, nickel, silica, rare earth, and strontium.
10. Stereo—Includes gold, iron, nickel, beryllium, and petroleum products.
11. Compact Disc—Includes aluminum and petroleum products.
12. Metal Chest—Includes iron and nickel. The brass trim is made of copper and zinc.
13. Carpet—Includes limestone, petroleum products, and selenium.
14. Drywall—Includes gypsum clay, vermiculite, calcium carbonate, and micas.

FIGURE 15.1 Minerals found in a typical office *(Modified after U.S. Geological Survey Circular 1289–2006)*

Minerals can be considered our nonrenewable heritage from the geologic past. Although new deposits are forming from present Earth processes, these processes are too slow to be of use to us today. Mineral deposits tend to be hidden in small areas. Deposits must, therefore, be discovered; unfortunately, most of the easy-to-find deposits have already been exploited. If our civilization, with its science and technology, were to vanish, future civilizations would have a much harder time discovering minerals than our ancestors did. Unlike biological resources, which are renewable, minerals are consumed and cannot be managed with the assumption that Earth processes will replace the source in a useful period of time. Recycling and conservation will help extend our mineral resources, but eventually the supply will be exhausted.

Resources and Reserves

Mineral resources can be defined broadly as elements, compounds, minerals, or rocks concentrated in a form that can be extracted to obtain a usable commodity. From a practical viewpoint, this definition is unsatisfactory because a resource will not normally be extracted unless extraction can be accomplished at a profit. A more pragmatic definition is that a mineral **resource** is a concentration of a naturally occurring material (i.e., solid, liquid, or gas) in or on the crust of Earth in a form that can now or *potentially* be extracted at a profit. A **reserve** is the portion of a resource that is identified and is *currently* available to be legally extracted at a profit. The distinction between resources and reserves, therefore, is based on current geologic, economic, and legal factors (**Figure 15.2**).[5]

Not all resource categories are reserves (Figure 15.2). As an analogy to help clarify this point, think about your personal finances. Your reserves are your liquid assets, such as money in your pocket or in the bank, whereas your resources include the total income you can expect to earn during your lifetime. This distinction is often critical to you because resources are "frozen" assets or next year's income and cannot be used to pay this month's bills.[5]

Silver's value as a reserve can illustrate some important points about resources and reserves. Earth's crust contains almost 2 trillion metric tons of silver. This is Earth's crustal resource of silver—an amount much larger than the annual world use, which is approximately 10,000 metric tons. If this silver existed as pure metal concentrated into one large mine, it would represent a supply sufficient for several hundred million years, at current levels of use. Most of this silver, however, exists in extremely low concentrations—too low to be extracted economically with current technology. The known reserve of silver, reflecting the amount we could obtain immediately with known techniques, is about 200,000 metric tons, or a 20-year supply at current use levels.

Availability and Use of Mineral Resources

The availability of a mineral in a certain form, in a certain concentration, and in a certain total amount at that concentration is determined by Earth's history—and is therefore a geologic topic. Types of mineral resources and the limits of their availability are technological and social questions that we will consider here.

Types of Mineral Resources. Some mineral resources are necessary for life. One example is salt, or halite (NaCl). Primitive peoples traveled long distances to obtain salt when it was not available locally. Salt today is as important as ever, and it has important medical uses as a vehicle to deliver chemicals, such as iodine to help prevent goiter (a thyroid disease). The iodine is added to the salt, which most people use on their food. Fluoride may be added to salt to help prevent dental cavities, and medication can be added to salt to fight malaria and lymphatic filariasis (a disfiguring disease caused by worms that has infected more than 120 million people, mostly in Asia, Africa, and South America).[6] Other mineral resources, such as diamonds, are desired for their beauty, and many more are necessary for producing and maintaining a certain level of technology.

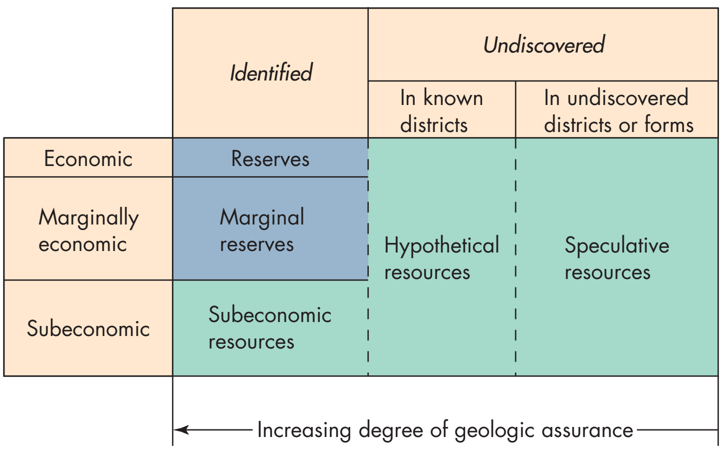


FIGURE 15.2 Resources and reserves Classification of mineral resources used by the U.S. Geological Survey and the U.S. Bureau of Mines. *(After U.S. Geological Survey Circular 831)*

Earth's mineral resources can be divided into several broad categories, based on how we use them:

- Elements for metal production and technology, which can be classified according to their abundance. The abundant metals include iron, aluminum, chromium, manganese, titanium, and magnesium. Iron and aluminum account for about 3% (by weight) of all minerals mined in the U.S. Scarce metals include copper, lead, zinc, tin, gold, silver, platinum, uranium, mercury, and molybdenum.
- Building materials such as *aggregate* sand, gravel, and crushed stone for concrete; clay for tile; and volcanic ash for cinder blocks to construct walls of buildings. These account for about 94 percent (by weight) of all minerals mined in the United States.
- Minerals for the chemical industry, such as the many minerals used in the production of petrochemicals, which are materials produced from natural gas or crude oil, such as plastics.
- Minerals for agriculture, such as fertilizers. Phosphate rock accounts for about 1 percent (by weight) of all minerals mined in the United States.

When we think of mineral resources, we usually think of the metals used in structural materials, but, in fact, with the exception of iron, the predominant mineral resources are not metals. Consider the annual world consumption of a few selected elements. Sodium and iron are used at a rate of approximately 100 million to 1,000 million tons per year. Nitrogen, sulfur, potassium, and calcium are used at a rate of approximately 10 million to 100 million tons per year. These four elements are used primarily as soil conditioners or fertilizers. Zinc, copper, aluminum, and lead have annual world consumption rates of about 3 million to 10 million tons, whereas gold and silver have annual consumption rates of 10,000 tons or less. Of the metallic minerals, iron makes up 95 percent of all the metal consumed; nickel, chromium, cobalt, and manganese are used mainly in alloys of iron, such as stainless steel, which are mixtures of iron and other elements. Therefore, we can conclude that nonmetallic mineral resources, with the exception of iron, are consumed at much greater rates than elements used for their metallic properties.

Responses to Limited Availability. The fundamental problem associated with the availability of mineral resources is not actual exhaustion or extinction; rather, it is the cost of maintaining an adequate reserve, or stock, within an economy, through mining and recycling. At some point, the costs of mining exceed the worth of the material. When the availability of a particular mineral becomes a limitation, several solutions are possible:

- Find more sources.
- Find a substitute.
- Recycle what has already been obtained.
- Use less and make more efficient use of what we have.
- Do without.

We can use a particular mineral resource in several ways: rapid consumption, consumption with conservation, or consumption and conservation with recycling. The option selected depends, in part, on economic, political, and social criteria. However, as more resources become limited, increased conservation and recycling are occurring, and the trend toward recycling is well established for metals such as copper, lead, and aluminum.

As the world population and the desire for a higher standard of living increase, the demand for mineral resources expands at a faster and faster rate. The United States has only 5 percent of Earth's population, yet we consume a disproportionate share of mineral resources, including the majority of the aluminum, copper, and nickel. If the world per capita consumption rate of these metals were to rise to the U.S. level, production would have to increase to several times the present rate. Because such an increase in production is very unlikely, affluent countries will have to find substitutes for some minerals or use a smaller proportion of the world annual production. Fortunately, these alternatives are being implemented. For example, in the United States, per capita nonfuel mineral consumption decreased significantly between about 1980 and 2010.

Domestic supplies of many mineral resources in the United States and other affluent nations are insufficient for current use and must be supplemented by imports from other nations. For example, the United States imports nearly all the graphite, manganese, strontium, tin, platinum, and chromium that we use in industrial and other processes. Industrial countries are particularly concerned about

the possibility that the supply of a much-desired or needed mineral may become interrupted by political, economic, or military instability of the supplying nation. The United States and many other countries and regions, including Western Europe, Japan, and, more recently, China and India, are currently dependent on a steady supply of imports to meet the mineral demand of industry. Of course, the fact that a mineral is imported into a country does not mean that it does not exist within the country in quantities that could be mined. Rather, it suggests that there are economic, political, or environmental reasons that make it easier, more practical, or more desirable to import the material.

15.2 Geology of Mineral Resources

The geology of mineral resources is intimately related to how Earth works through plate tectonics and the rock cycle (see Chapters 2 and 3), and nearly all aspects of geologic processes are involved to some extent in producing local concentrations of useful materials.

Local Concentrations of Metals

The term **ore** is sometimes applied to natural occurring minerals that can be extracted for a profit. Locations where ore is found have anomalously high concentrations of these minerals. The concentration of metal necessary for a particular mineral to be classified as an ore varies with technology, economics, and politics. Before smelting (i.e., extraction of metal by heating) was invented, the only metal ores were those in which the metals appeared in their pure form; gold, for example, was originally obtained as a pure, or native, metal. Now gold mines extend deep beneath the surface, and the recovery process involves reducing tons of rock to ounces of gold. Although the rock contains only a minute amount of gold, we consider it a gold ore because we can extract the gold profitably.

The **concentration factor** of a metal is the ratio of its necessary concentration for profitable mining (i.e., of its concentration in ore) to its average concentration in Earth's crust. Table 15.1 lists some metallic elements and their average concentrations, concentrations in ore, and concentration factors. Aluminum, for example, has an average concentration of about 8 percent in Earth's crust, and needs to be found at concentrations of about 35 percent to be mined economically, giving it a concentration factor of about 4. Mercury, on the other hand, has an average concentration of only a tiny fraction of 1 percent and must have a concentration factor of about 10,000 to be mined economically. Nevertheless, mercury ores are common in certain regions, where they and other metallic ores are deposited (see A Closer Look: Plate Tectonics and Minerals). The percentage of a metal in ore (and thus the concentration factor) is subject to change as the demand for the metal changes.

TABLE 15.1 Approximate Concentration Factors of Selected Metals Necessary Before Mining Is Economically Feasible

Metal	Natural Concentration (percentage)	Percentage in Ore	Approximate Concentration Factor
Gold	0.0000004	0.001	2,500
Mercury	0.00001	0.1	10,500
Lead	0.0015	4	2,500
Copper	0.005	0.4 to 0.8	80 to 160
Iron	5	20 to 69	4 to 14
Aluminum	8	35	4

Data from U.S. Geological Survey Professional Paper 820, 1973.

A Closer Look

Plate Tectonics and Minerals

In a broadbrush approach to the geology of mineral resources, tectonic plate boundaries are related to the origin of such ore deposits as iron, gold, copper, and mercury **Figure 15.A**. Basically, ore deposits result from processes operating at the diverging and converging plate boundaries (see Chapter 2).

The origin of metallic ore deposits at divergent plate boundaries is related to the migration (i.e., movement) of ocean water. Cold, dense ocean water moves down through numerous fractures in the basaltic rocks at oceanic ridges and is heated by contact with or heat from nearby molten rock (i.e., magma). The warm water is lighter and more chemically active and rises up (i.e., convects) through the fractured rocks, leaching out metals. The metals are carried in solution and are deposited (i.e., precipitated as metallic sulfides), forming black smokers, which are chimney-shaped structures that emit black, mineral-charged hot water.[8] Numerous sulfide deposits have been discovered along oceanic ridges, and, undoubtedly, numerous others will be located. These are discussed further, along with minerals from the sea, in Section 15.2.

The origin of metallic ore deposits at convergent plate boundaries is hypothesized to be the result of the partial melting of seawater-saturated rocks of the oceanic lithosphere in a subduction zone. The high heat and pressure that cause the melting also facilitate the release and movement of metals from the partially molten rock. These metals, which originated in the rock, become concentrated and ascend as more fluid components of the magma. The metal-rich fluids are eventually released (or escape) from the magma, and the metals are deposited in a host rock.[7,9]

An example of metallic deposits at subduction zones is the global occurrence of known mercury deposits (**Figures 15.B**). All the belts of productive deposits of mercury are associated with volcanic systems and are located near convergent plate boundaries. It has been suggested that the mercury, originally found in oceanic sediments of the crust, is distilled out of the downward-plunging plate and emplaced at a higher level above the subduction zone.[8,9] The significant point, from an economic viewpoint, is that convergent plate junctions characterized by volcanism and tectonic activities are likely places to find mercury. A similar argument can be made for other ore deposits, but there is danger in oversimplification, insofar as many deposits are not directly associated with plate boundaries.

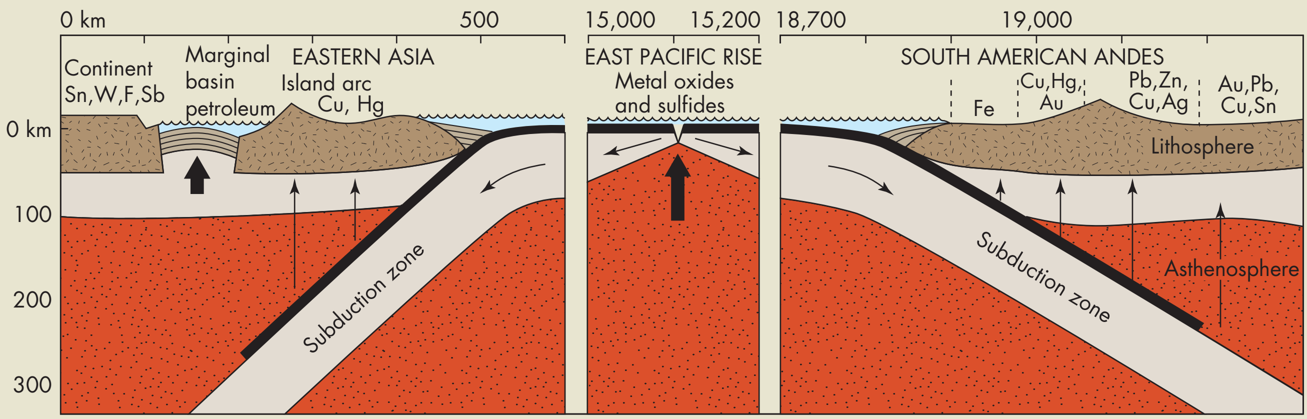


FIGURE 15.A Plate tectonics and mineral deposits Diagram of the relationship between the East Pacific Rise (divergent plate boundary), Pacific margins (convergent plate boundaries), and metallic ore deposits. *(After NOAA, California Geology 30(5), 1977 and revised in 2011)* Sn is tin; W is tungsten; F is fluorine; Sb is Antimony; Cu is Copper; Fe is iron; Au is gold; Ag is silver; Hg is mercury; Pb is lead; also see Table 3.1.

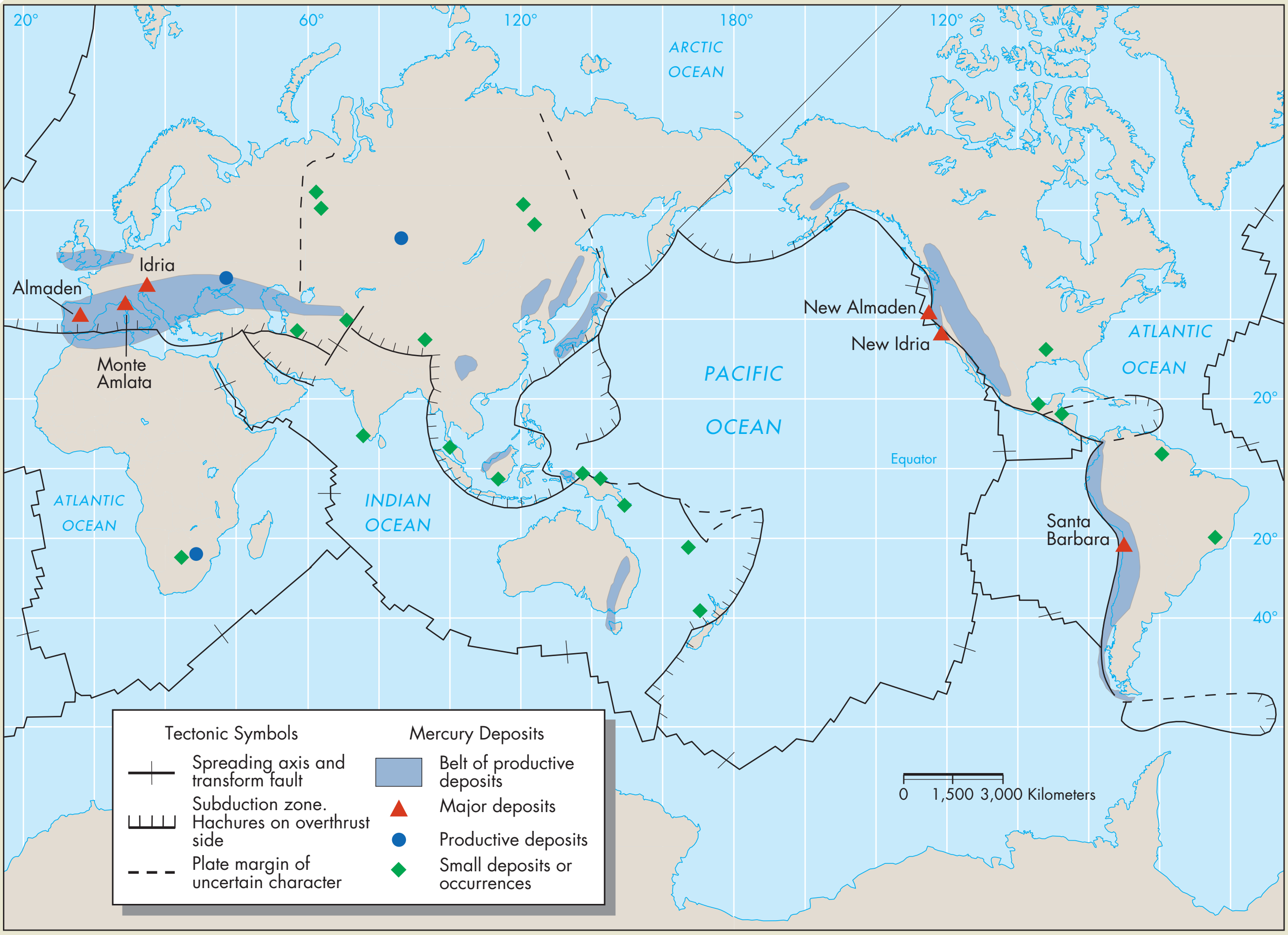


FIGURE 15.B Mercury deposits Relationship between mercury deposits and recently active subduction zones. *(From Brobst, D. A., and Pratt, W. P., eds. 1973. U.S. Geological Survey Professional Paper 820, updated 2010)*

Mineral resources with commercial value can be classified into several categories, based on geologic processes of formation:

- *Igneous processes*, including crystal settling, late magmatic process, and hydrothermal replacement
- *Metamorphic processes* associated with contact or regional metamorphism
- *Sedimentary processes*, including accumulation in oceanic, lake, stream, wind, and glacial environments
- *Biological processes*
- *Weathering processes*, such as soil formations and in situ (i.e., in-place) concentrations of insoluble minerals in weathered rock debris

Table 15.2 lists examples of ore deposits from each of these categories.

Igneous Processes

Most ore deposits, caused by igneous processes, result from an enrichment process that concentrates an economically desirable ore of metals, such as copper, nickel, or gold. In some cases, however, an entire igneous rock mass contains disseminated crystals that can be recovered economically. Perhaps the best-known example is the occurrence of diamond crystals, found in a coarse-grained igneous rock called *kimberlite*, which characteristically occurs as a pipe-shaped body of rock that decreases in diameter with depth (**Figure 15.3**, page 510).

TABLE 15.2 Examples of Different Types of Mineral Resources

Type	Example
Igneous	
Disseminated	Diamonds—South Africa
Crystal settling	Chromite—Stillwater, Montana
Late magmatic	Magnetite—Adirondack Mountains, New York
Pegmatite	Beryl and lithium—Black Hills, South Dakota
Hydrothermal	Copper—Butte, Montana
Metamorphic	
Contact metamorphism	Lead and silver—Leadville, Colorado
Regional metamorphism	Asbestos—Quebec, Canada
Sedimentary	
Evaporite (lake or ocean)	Potassium—Carlsbad, New Mexico
Placer (stream)	Gold—Sierra Nevada foothills, California
Glacial	Sand and gravel—northern Indiana
Deep-ocean	Manganese oxide nodules—central and southern Pacific Ocean
Biological	
	Phosphorus—Florida
Weathering	
Residual soil	Bauxite—Arkansas
Secondary enrichment	Copper—Utah

Modified from Robert J. Foster. 1983. *General Geology*, 4th ed. Columbus, OH: Charles E. Merrill.

Almost the entire kimberlite pipe is the ore deposit, and the diamond crystals are disseminated throughout the rock.[7]

Diamonds, which are composed of carbon, form at very high temperatures and pressures, perhaps at depths as great as 190 km—well below the crust of Earth and into the mantle. Some kimberlite pipes in South Africa are believed to be as old as 2 billion years. Near the surface, diamonds are not stable over geologic time and will eventually change to graphite (the mineral in "lead" pencils). Do not sell your diamonds yet! The transformation won't happen at surface temperature and pressure, and, as a result, diamonds are metastable, remaining beautiful and mysterious for periods of time of interest to humans. The fact that the kimberlite pipes are so old suggests that they must be intruded (i.e., moved upward) from deep diamond-forming depth to near the surface relatively quickly. If this were not the case, the diamonds would have been transformed to graphite.

Crystal Settling. Concentrated ore deposits can result from igneous processes called *crystal settling* that segregate crystals formed earlier from those formed later. For example, as magma cools, heavy minerals that crystallize early may slowly sink or settle toward the lower part of the magma chamber, where they form concentrated layers. Deposits of chromite (i.e., ore of chromium) have formed by this process (**Figure 15.4**).

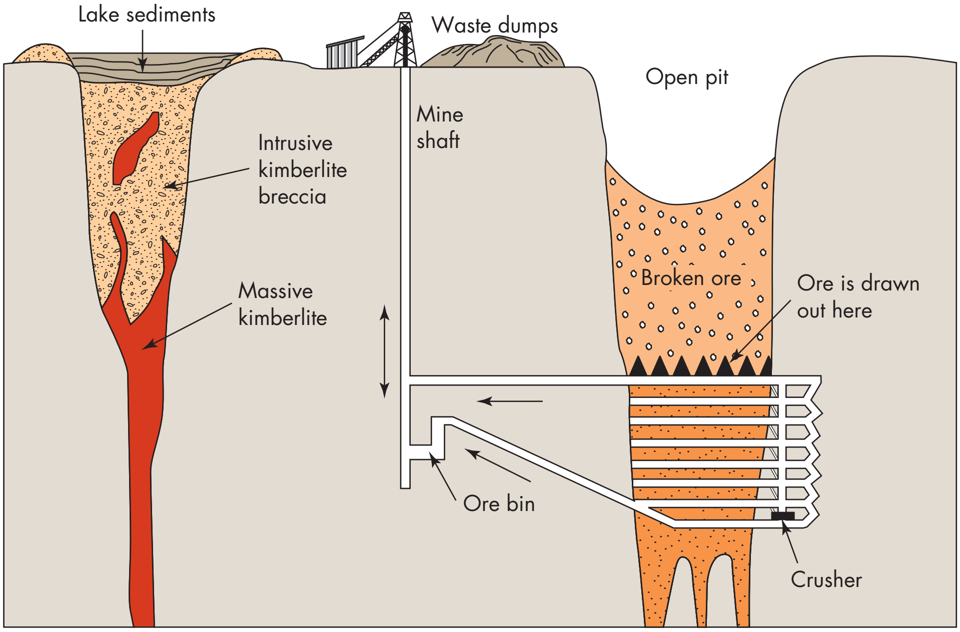


FIGURE 15.3 Diamond pipe (a) Idealized diagram showing a typical South African diamond pipe and mine. Diamonds are scattered throughout the cylindrical body of igneous rock, kimberlite. *(From Kesler, S. E. 1994.* Mineral Resources, Economics and the Environment. *New York: Macmillan)* (b) Aerial view of diamond mine, Kimberly, South Africa. This is one of the largest hand-dug excavations in the world. *(Helen Thompson/Animals Animals/Earth Scenes)*

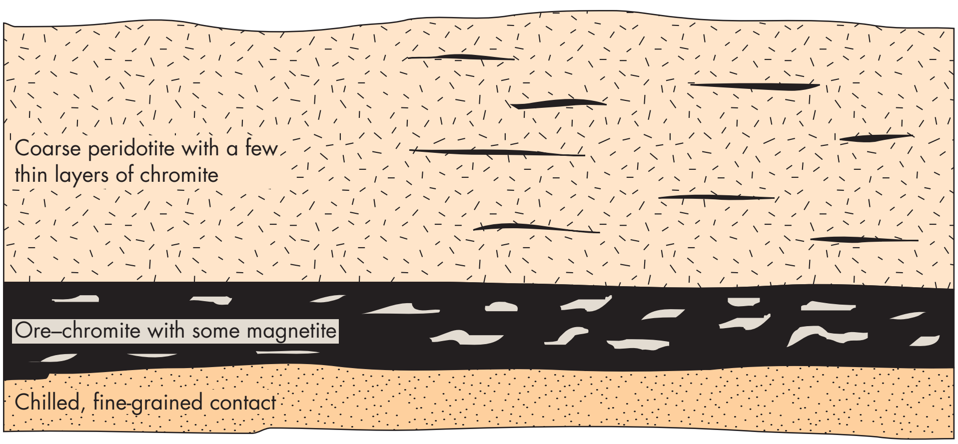


FIGURE 15.4 How chromite layers might form The chromite crystallizes early, and the heavy crystals sink to the bottom and accumulate in layers. *(From Foster, R. J. 1983.* General Geology, *4th ed. Columbus, OH: Charles E. Merrill)*

Late Magmatic Processes and Hydrothermal Replacement. Late magmatic processes occur after most of the magma has crystallized and rare and heavy metalliferous materials in water- and gas-rich solutions remain. This late-stage metallic solution may be squeezed into fractures or settle into interstices (i.e., empty spaces) between earlier-formed crystals. Other late-stage solutions form coarse-grained igneous rock known as *pegmatite,* which is rich in feldspar, mica, and quartz, as well as certain rare minerals. Pegmatites have been extensively mined for feldspar, mica, spodumene (i.e., lithium mineral), pure quartz for silicon chips and clay that forms from weathered feldspar.

Hydrothermal (i.e., hot-water) mineral deposits are a common type of ore deposit. They originate from late-stage magmatic processes and give rise to a variety of mineralization, including gold, silver, copper, mercury, lead, zinc, and other metals, as well as many nonmetallic minerals. The hydrothermal solutions that form ore deposits are mineralizing fluids that migrate through a host rock, crystallizing as veins or small dikes (**Figure 15.5**). The mineral material is either produced directly from the igneous parent rock or altered by metamorphic processes, as magmatic solutions intrude into the surrounding rock. (Alteration by metamorphic processes, called *contact metamorphism*, is discussed with metamorphic processes, later in this chapter.) Many hydrothermal deposits cannot be traced to a parent igneous rock mass, however, and their origin remains unknown. It is speculated that circulating groundwater, heated and enriched with minerals after contact with deeply buried magma, might be responsible for some of these deposits.[7,8]

Hydrothermal deposits are of two types: cavity-filling and replacement. *Cavity-filling deposits* are formed when hydrothermal solutions migrate along openings in rocks (e.g., fracture systems, pore spaces, bedding planes) and precipitate (i.e., crystallize) ore minerals. *Replacement deposits* form as hydrothermal solutions react with the host rock, forming a zone in which ore minerals precipitate from the mineralizing fluids and replace part of the host rock. Although replacement deposits are believed to dominate at higher temperatures and pressures than cavity-filling deposits, both may be found in close association as one grades into the other; that is, the filling of an open fracture by precipitation from hydrothermal solutions may occur simultaneously with replacement of the rock that lines the fracture.[8]

Hydrothermal replacement processes are significant because, excluding some iron and nonmetallic deposits, they have produced some of the world's largest and most important mineral deposits. Some of these deposits result from a massive, nearly complete replacement of host rock with ore minerals that terminate abruptly; others form thin replacement zones along fissures; and still others form disseminated replacement deposits that may involve huge amounts of relatively low-grade ore.[7,8]

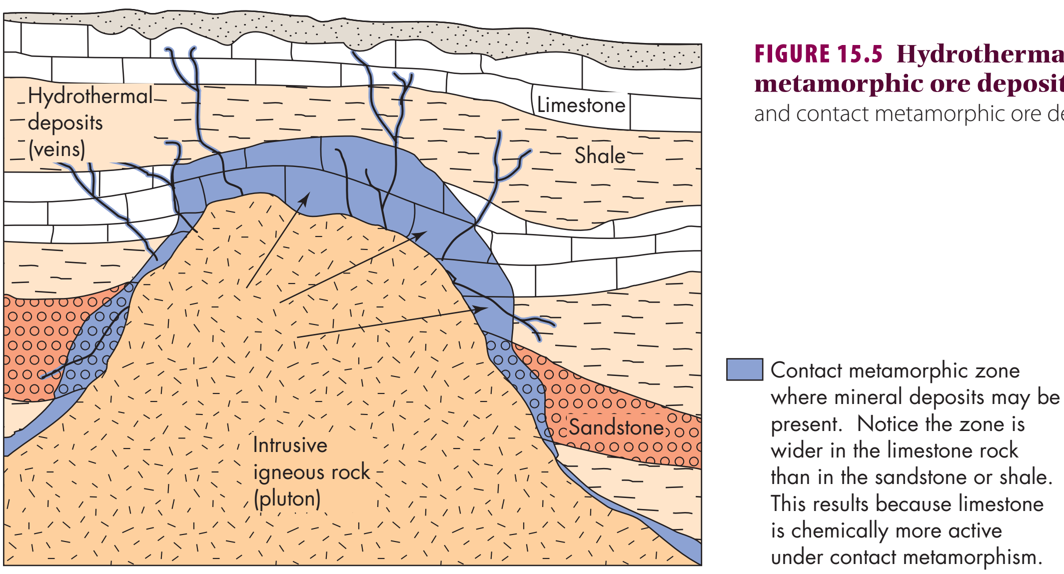


FIGURE 15.5 Hydrothermal and contact metamorphic ore deposits How hydrothermal and contact metamorphic ore deposits might form.

The actual sequence of geologic events leading to the development of a hydrothermal ore deposit is usually complex. Consider, for example, the tremendous, disseminated copper deposits of northern Chile. The actual mineralization is thought to be related to igneous activity, faulting, and folding that occurred 60 million to 70 million years ago. The ore deposit is an elongated, tabular mass along a highly sheared (i.e., fractured) zone separating two types of granitic rock. The concentration of copper results from a number of factors:

- A source igneous rock supplied the copper.
- The fissure zone tapped the copper supply and facilitated movement of the mineralizing fluids.
- The host rock was altered and fractured, preparing it for deposition and replacement processes that produced the ore.
- The copper was leached and redeposited again by meteoric water, which further concentrated the ore.[7,8]

Metamorphic Processes

Contact Metamorphism. Ore deposits are often found along the contact between igneous rocks and the surrounding rocks they intrude. This area is characterized by **contact metamorphism**, caused by the heat, pressure, and chemically active fluids of the cooling magma interacting with the surrounding rock, called *country rock*, or *host rock*. The width of the contact metamorphic zone varies with the type of country rock, as shown in Figure 15.5. The zone is usually thickest in limestone because limestone is more reactive: The release of carbon dioxide (CO_2) increases the mobility of reactants. The zone is generally thinnest for shale because the fine-grained texture retards the movement of hot, chemically active solutions, and the zone is intermediate for sandstone. As we have already mentioned, some of the mineral deposits that form in contact areas originate from the magmatic fluids and some from reactions of these fluids with the country rock.

Regional Metamorphism. Metamorphism can also result from regional increase of temperature and pressure associated with deep burial of rocks or tectonic activity. This **regional metamorphism** can change the mineralogy and texture of the preexisting rocks, producing ore deposits of asbestos, talc, graphite, and other valuable nonmetallic deposits.[7–9]

Metamorphism has been suggested as a possible origin of some hydrothermal fluids. It is a particularly likely cause in high-temperature, high-pressure zones, where fluids might be produced and forced out into the surrounding rocks to form replacement or cavity-filling deposits. For example, the native copper found along the top of ancient basalt flows in the Michigan copper district was apparently produced by metamorphism and alteration of the basalt, which released the copper and other materials that produced the deposits.[7–9]

Our discussion of igneous and metamorphic processes has focused primarily on ore deposits. However, igneous and metamorphic processes are also responsible for producing a good deal of stone used in the construction industry. Granite, basalt, marble (i.e., metamorphosed limestone), slate (i.e., metamorphosed shale), and quartzite (i.e., metamorphosed sandstone), along with other rocks, are quarried to produce crushed rock and dimension stone in the United States. Stone is used in many aspects of construction work, and many people are surprised to learn that, in total value, with the exception of iron and steel, the stone industry is one of the largest nonfuel mineral industries in the United States (Table 15.2).[4]

Sedimentary Processes

Sedimentary processes are often significant in concentrating economically valuable materials in sufficient amounts for extraction. As sediments are transported, wind and running water help segregate the sediment by size, shape, and density. Thus, the best sand or sand and gravel deposits for construction purposes are those in which the finer materials have been removed by water or wind. Sand dunes, beach deposits, and deposits in stream channels are good examples.

Sand and Gravel. The U.S. sand and gravel industry in 2010 amounted to about $7 billion, and, by volume mined (about 800 million tons). It is one of the largest nonfuel mineral industries in the United States. Currently, most sand and gravel are obtained from river channels and water-worked

glacial deposits. The United States now produces more sand and gravel than it needs.

Environmental restrictions on extraction are causing sand and gravel operations to move away from areas with high population density, and shortages of sand and gravel are expected to increase as zoning and land development restrict locations where they may be extracted. Extraction from river channels and active floodplains can cause degradation to the river environment, and objections to river extraction operations are becoming more common.

Placer Deposits. Stream processes transport and sort all types of materials according to size and density. Therefore, if the bedrock in a river basin contains heavy metals such as gold, streams draining the basin may concentrate heavy metals to form **placer deposits** (i.e., ore formed by deposit of sediments) in areas where there is reduced turbulence or velocity of flow, such as between particles on riffles, in open crevices or fractures at the bottoms of pools, or at the inside curves of bends (Figure 15.6). Placer

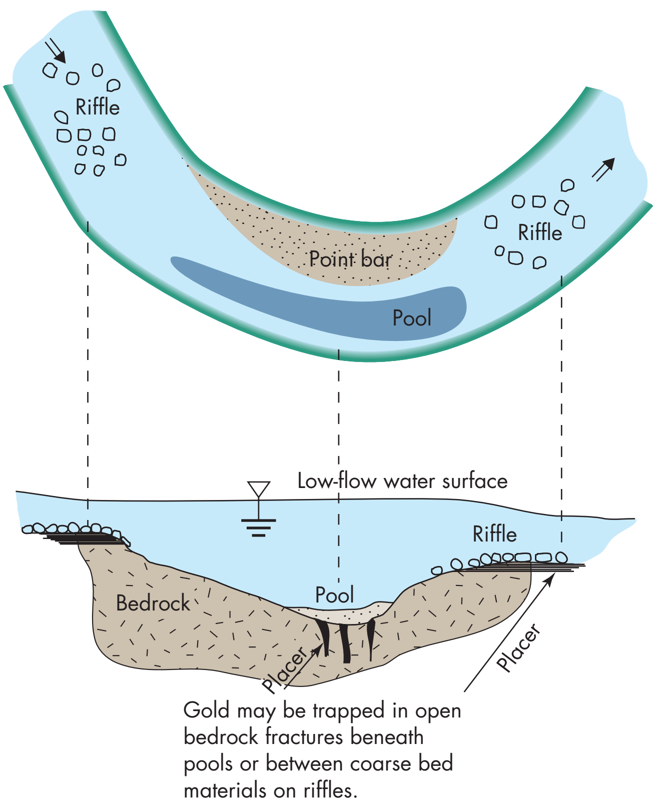


FIGURE 15.6 Placer gold Diagram of a stream channel and bottom profile, showing areas where placer deposits of gold are likely to occur.

mining of gold—known as a "poor man's method" because a miner needed only a shovel, a pan, and a strong back to work the streamside claim—helped to stimulate settlement of California, Alaska, and other areas of the United States. Furthermore, the gold in California attracted miners who acquired the expertise necessary to locate and develop other resources in the western conterminous United States and Alaska. Placer deposits of gold and diamonds have also been concentrated by coastal processes, primarily wave action. Beach sands and near-shore deposits are mined in Africa and other places.

Evaporite Deposits. Rivers and streams that empty into the oceans and lakes carry tremendous quantities of dissolved material derived from the weathering of rocks. From time to time, geologically speaking, a shallow marine basin may be isolated by tectonic activity (i.e., uplift) that restricts circulation and facilitates evaporation. In other cases, climatic variations during the ice ages produced large inland lakes with no outlets, which eventually dried up. In either case, as evaporation progresses, the dissolved materials precipitate, forming a wide variety of compounds, minerals, and rocks called **evaporite** deposits that have important commercial value.

Most evaporite deposits can be grouped into one of three types: *marine evaporites* (solids)—potassium and sodium salts, calcium carbonate, gypsum, and anhydrite; *nonmarine evaporites* (solids)—sodium and calcium carbonate, sulfate, borate, nitrate, and limited iodine and strontium compounds; and *brines* (liquids derived from wells, thermal springs, inland salt lakes, and seawaters)—bromine, iodine, calcium chloride, and magnesium. Heavy metals (e.g., copper, lead, zinc) associated with brines and sediments in the Red Sea, Salton Sea, and other areas are important resources that may be exploited in the future. Extensive marine evaporite deposits exist in the United States (Figure 15.7). The major deposits are halite (i.e., common salt, NaCl), gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), and interbedded limestone ($CaCO_3$). Limestone, gypsum, and anhydrite are present in nearly all marine evaporite basins, and halite and potassium minerals are found in a few. Evaporite materials are widely used in industry and agriculture.[11]

Marine evaporites can form stratified deposits that may extend for hundreds of kilometers, with a

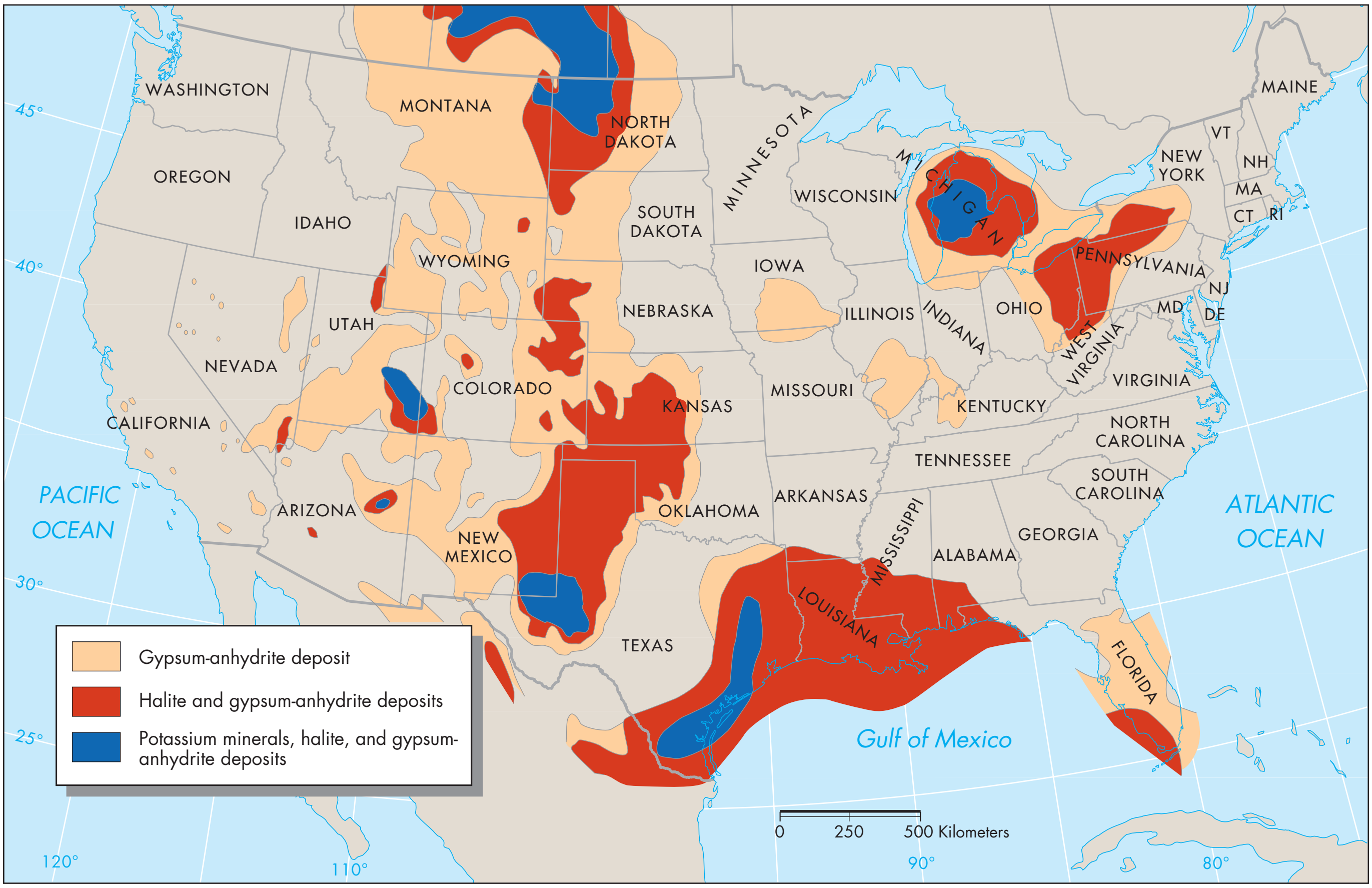


FIGURE 15.7 Marine evaporite deposits in the United States *(After Brobst, D. A., and Pratt, W. P., eds. 1973. U.S. Geological Survey Professional Paper 820)*

thickness of several thousand meters. The evaporites represent the product of evaporation of seawater in isolated shallow basins with restricted circulation. Within many marine evaporite basins, the different deposits are arranged in broad zones that reflect changes in salinity and other factors controlling the precipitation of evaporites; that is, different materials may be precipitated at the same time in different parts of the evaporite basin. Halite, for example, is precipitated in areas where the brine is more saline, and gypsum is precipitated where it is less saline. Economic deposits of potassium evaporite minerals are relatively rare but may form from highly concentrated brines.

Nonmarine evaporite deposits form by evaporation of lakes in a closed basin. Tectonic activity, such as faulting, can produce an isolated basin with internal drainage and no outlet. However, to maintain a favorable environment for evaporite mineral precipitation, the tectonic activity must continue to uplift barriers across possible outlets or lower the basin floor faster than sediment can raise it. Even under these conditions, economic deposits of evaporites will not form unless sufficient dissolved salts have washed into the basin by surface runoff from surrounding highlands (**Figure 15.8**). Finally, even if all favorable environmental criteria are present, including an isolated basin with sufficient runoff and dissolved salts, valuable nonmarine evaporates, such as sodium carbonate or borate, will not form unless the geology of the highlands surrounding the basin is also favorable and yields runoff with sufficient quantities of the desired material in solution.[11]

Some evaporite beds are compressed by overlying rocks and mobilized, and then they pierce or intrude the overlying rocks. Intrusions of salt, called **salt domes**, are quite common in the Gulf Coast of the United States and are also found in northwestern Germany, Iran, and other areas. Salt

FIGURE 15.8 White salt deposits forming in Death Valley, California The salt is deposited as the water evaporates. *(konstantin32/iStockphoto)*

domes in the Gulf Coast are economically important for two reasons:

- They are a good source for nearly pure salt. Some have extensive deposits of elemental sulfur (**Figure 15.9**).
- Some have oil reserves on their flanks.

Salt domes are also environmentally important as possible permanent disposal sites for radioactive waste, although, because salt domes tend to be mobile, their suitability as disposal sites for hazardous wastes must be seriously questioned.

Evaporites from brine resources of the United States are substantial (**Table 15.3**), assuring that no shortage is likely for a considerable period of time. But many evaporites will continue to have a *place value* because transportation of these mineral commodities increases their price, so continued discoveries of high-grade deposits closer to where they will be consumed remains an important goal.[11]

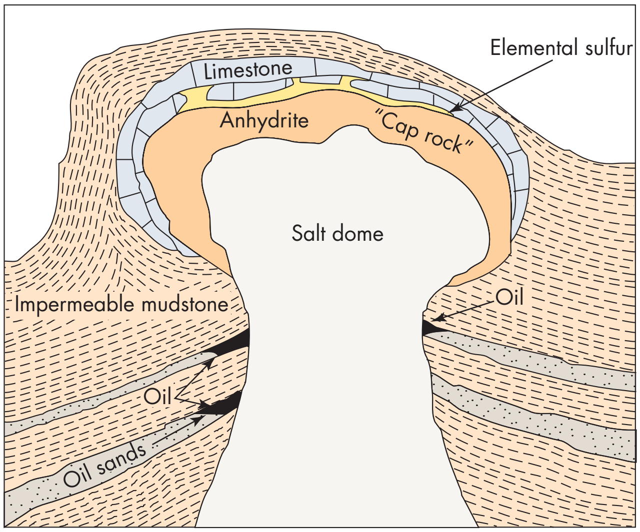


FIGURE 15.9 Salt dome A cross section through a typical salt dome of the type found in the Gulf Coast of the United States.

Biological Processes

Organisms are able to form many kinds of minerals, such as the various calcium and magnesium carbonate minerals in shells and calcium phosphate in bones. Some of these minerals cannot be formed inorganically in the biosphere. Thirty-one different biologically produced minerals have been identified. Minerals of biological origin contribute significantly to sedimentary deposits.[12]

An interesting example of mineral deposits produced by biological processes is phosphates associated with sedimentary marine deposition. Phosphorus-rich sedimentary rocks are fairly common in some of the western states, as well as in Tennessee, North Carolina, and Florida. The common phosphorus-bearing mineral in these rocks is apatite, a calcium phosphate associated with bones and teeth. Fish and other marine organisms extract the phosphate from seawater to form apatite, and the mineral deposit results from sedimentary accumulations of the

TABLE 15.3 Evaporite and Brine Resources of the United States, Expressed in Years of Supply at Current Rates of Domestic Consumption

Commodity	Identified Resources[1] (reserves[2] and subeconomic deposits)	Undiscovered Resources (hypothetical[3] and speculative[4] resources)
Potassium compound	100 years	Virtually inexhaustible
Salt	1000+ years	Unlimited
Gypsum and anhydrite	500+ years	Virtually inexhaustible
Sodium carbonate	6000 years	5000 years
Sodium sulfate	700 years	2000 years
Borates	300 years	1000 years
Nitrates	Unlimited (air)	Unlimited (air)
Strontium	500 years	2000 years
Bromine	Unlimited (seawater)	Unlimited (seawater)
Iodine	100 years	500 years
Calcium chloride	100+ years	1000+ years
Magnesium	Unlimited (seawater)	Unlimited (seawater)

[1]Identified resources: Specific, identified mineral deposits that may or may not be evaluated as to extent and grade and whose contained minerals may or may not be profitably recovered with existing technology and economic conditions.

[2]Reserves: Identified deposits from which minerals can be extracted profitably with existing technology and under present economic conditions.

[3]Hypothetical resources: Undiscovered mineral deposits, whether of recoverable or subeconomic grade, that are geologically predictable as existing in known districts.

[4]Speculative resources: Undiscovered mineral deposits, whether of recoverable or subeconomic grade, that may exist in unknown districts or in unrecognized or unconventional form.

G. I. Smith, et al. 1973. U.S. Geological Survey Professional Paper 820.

phosphate-rich fish bones and teeth. The richest phosphate mine in the world, known as "Bone Valley," is located about 40 km east of Tampa, Florida (**Figure 15.10**). The deposit is marine sedimentary rocks composed in part of fossils of marine animals that lived 10 to 15 million years ago, when Bone Valley was the bottom of a shallow sea. That deposit has supplied as much as one-third of the world's phosphate production.

Another important source of phosphorus is guano (i.e., bird feces), which accumulates where there are large colonies of nesting sea birds and a climate arid enough for the guano to dry to a rocklike mass. Thus, the formation of one of the major sources of phosphorus depends upon unique biological and geographical conditions.

FIGURE 15.10 Large open-pit phosphate mine in Florida Piles of mining waste with standing water dominate the landscape shown here. Some land has been reclaimed for use as pasture in the upper part of the photograph. *(Phillippe Diederich/The New York Times/Redux Pictures)*

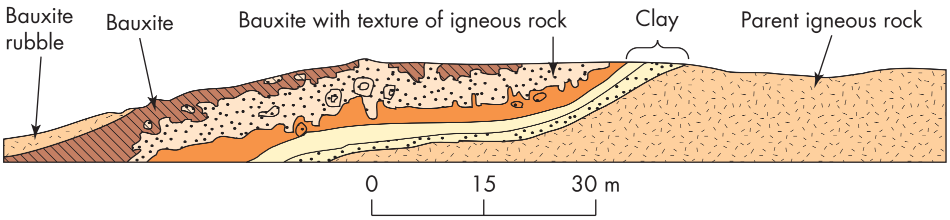


FIGURE 15.11 Aluminum ore Cross section of the Pruden bauxite mine, Arkansas. The bauxite was formed by intensive weathering of the aluminum-rich igneous rocks. *(After G. Mackenzie, Jr., et al. 1958. U.S. Geological Survey Professional Paper 299)*

Weathering Processes

Weathering is responsible for concentrating some materials to the point at which they can be extracted at a profit. Weathering processes can produce residual ore deposits in the weathered material and provide secondary enrichment of low-grade ore.

Residual Ore Deposits. Intensive weathering of rocks and soils can produce residual deposits of the less soluble materials, which may have economic value. For example, intensive weathering of some rocks forms a type of soil known as *laterite* (a residual soil derived from aluminum- and iron-rich igneous rocks). The weathering processes concentrate relatively insoluble hydrated oxides of aluminum and iron, while more soluble elements, such as silica, calcium, and sodium, are selectively removed by soil and biological processes. If sufficiently concentrated, residual aluminum oxide forms an aluminum ore known as **bauxite** (Figure 15.11). Important nickel and cobalt deposits are also found in laterite soils, developed from ferromagnesian-rich igneous rocks.[13]

Insoluble ore deposits, such as native gold, are generally residual, meaning that unless they are removed by erosion, they accumulate in weathered rock and soil. Accumulation of the insoluble ore minerals is favored where the parent rock is a relatively soluble material, such as limestone (Figure 15.12). Care must be taken in evaluating a residual weathered rock or soil deposit because the near-surface concentration may be a much higher grade than ore in the parent, unweathered rocks.

Secondary Enrichment. Weathering is also involved in *secondary enrichment* processes to produce sulfide ore deposits from low-grade primary ore.

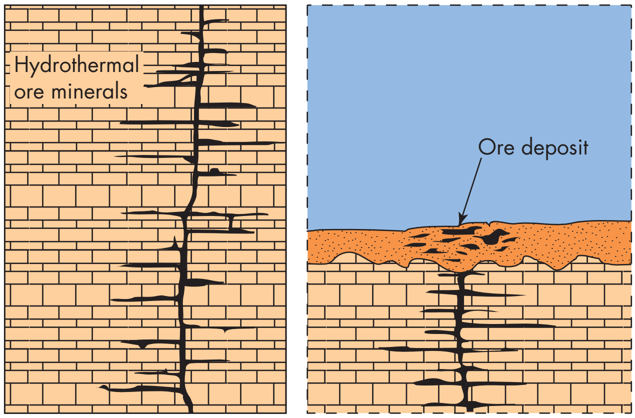


FIGURE 15.12 Residual ore deposit How an ore deposit of insoluble minerals might form by weathering and formation of a residual soil. As the limestone that contained the deposit weathered, the ore minerals became concentrated in the residual soil. *(From Foster, R. J. 1983.* General Geology, *4th ed. Columbus, OH: Charles E. Merrill)*

Near the surface, primary ore containing such minerals as iron, copper, and silver sulfides is in contact with slightly acid soil water in an oxygen-rich environment. As the sulfides are oxidized, they are dissolved, forming solutions rich in sulfuric acid and in silver and copper sulfate; these solutions migrate downward, producing a leached zone devoid of ore minerals. Figure 15.13 shows a primary ore that has already undergone oxidation and leaching. Below the leached zone, oxidation continues, as the sulfate solutions continue to move toward the groundwater table. Below the water table, if oxygen is no longer available, the solutions are deposited as sulfides, increasing the metal content of the primary ore as much as tenfold. In this way, low-grade primary ore is rendered more valuable, and high-grade primary ore is made even more attractive.[7,8]

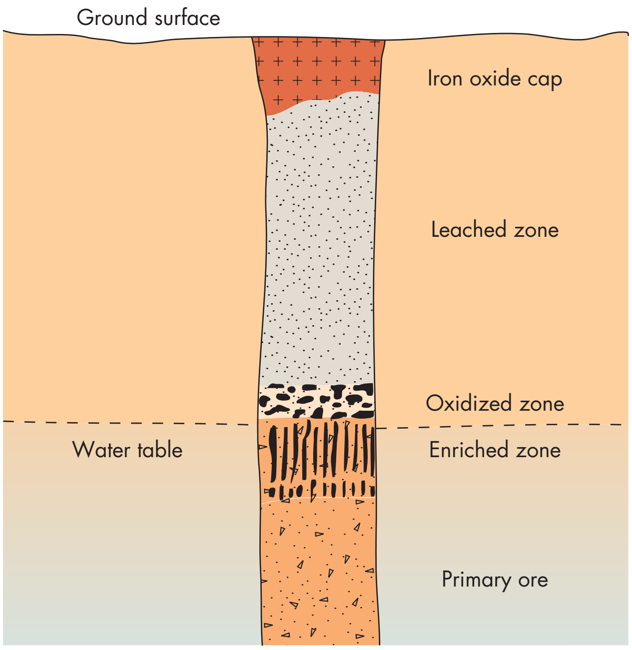


FIGURE 15.13 Secondary enrichment Typical zones that form during secondary enrichment processes. Sulfide ore minerals in the primary ore vein are oxidized and altered and then are leached from the oxidized zone and redeposited in the enriched zone. The iron oxide cap is generally a reddish color and may be helpful in locating ore deposits that have been enriched. *(From Foster, R. J.* 1983. General geology, *4th ed. Columbus, OH: Charles E. Merrill)*

The presence of a residual iron oxide cap at the surface indicates the possibility of an enriched ore below, but it is not always conclusive. Of particular importance to the formation of a zone of secondary enrichment is the presence in the primary ore of iron sulfide (e.g., pyrite). Without it, secondary enrichment seldom takes place because iron sulfide in the presence of oxygen and water forms sulfuric acid, which is a necessary solvent. Another factor favoring development of a secondary-enrichment ore deposit is the primary ore being sufficiently permeable to allow water and solutions to migrate freely downward. Given a primary ore that meets these criteria, the reddish iron oxide cap probably does indicate that secondary enrichment has taken place.[7,8]

Several disseminated copper deposits have become economically successful because of secondary enrichment, which concentrates dispersed metals. For example, secondary enrichment of a disseminated copper deposit at Miami, Arizona, increased the grade of the ore from less than 1 percent copper in the primary ore to as much as 5 percent in some localized zones of enrichment.[7,8]

Other Minerals from the Sea

Mineral resources in seawater or on the bottom of the ocean are vast and, in some cases, such as magnesium, nearly unlimited. In the United States, magnesium was first extracted from seawater in 1940. By 1972, one company in Texas produced 80 percent of our domestic magnesium, using seawater as its raw material source. Today, one company in Utah extracts magnesium from Great Salt Lake brines.

The deep-ocean floor may eventually be the site of a mineral rush. Identified deposits include massive sulfide deposits associated with hydrothermal vents, manganese oxide nodules, and cobalt-enriched manganese crusts.

Sulfide Deposits. Massive sulfide deposits containing zinc, copper, iron, and trace amounts of silver are produced at divergent plate boundaries (i.e., oceanic ridges) by the forces of plate tectonics. Pressure created by several thousand meters of water at ridges forces cold seawater deep into numerous rock fractures, where it is heated by upwelling magma to temperatures as high as 350°C. The pressure of the heated water produces vents known as *black smokers*, from which the hot, dark-colored, mineral-rich water emerges as hot springs (Figure 15.14). Circulating seawater leaches the surrounding rocks, removing metals that are deposited when the mineral-rich water is ejected into the cold sea. Sulfide minerals precipitate near the vents, forming massive towerlike formations that are rich in metals. The hot vents are of particular biological significance because they support a unique assemblage of animals, including giant clams, tubeworms, and white crabs. Ecosystems including these animals base their existence on sulfide compounds extruded from black smokers, existing through a process called *chemosynthesis*, as opposed to photosynthesis, which supports all other known ecosystems on Earth.

The extent of sulfide mineral deposits along oceanic ridges is poorly known, and, although leases to some possible deposits are being considered, it seems unlikely that such deposits will be extracted at a profit in the near future. Certainly, potential environmental degradation, such as decreased water quality and sediment pollution, will have to be carefully evaluated prior to any mining activity.

Study of the formation of massive sulfide deposits at oceanic ridges is helping geologists understand some of the mineral deposits on land. For example,

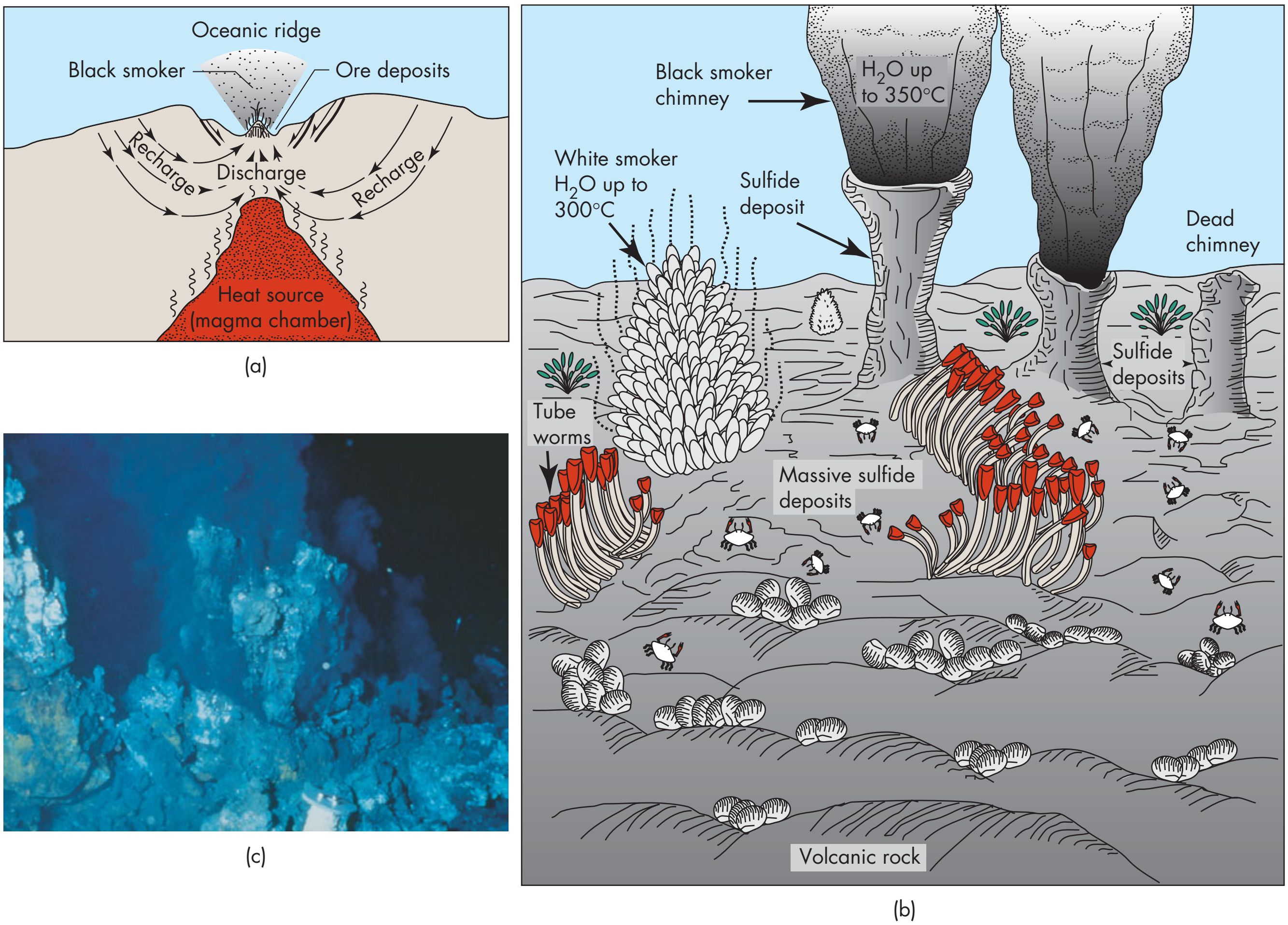


FIGURE 15.14 Oceanic ridge sulfide deposits (a) Oceanic ridge hydrothermal environment; (b) detail of black smokers where massive sulfide deposits form; (c) photograph of black smoker. *(R. Haymon/USGS)*

massive sulfide deposits being mined in Cyprus are believed to have formed at an oceanic ridge and to have been later uplifted to the surface.

Manganese Oxide Nodules. **Manganese oxide nodules** (Figure 15.15) cover vast areas of the deep-ocean floor. They contain manganese (24 percent) and iron (14 percent), with secondary copper (1 percent), nickel (1 percent), and cobalt (0.25 percent). Nodules are found in the Atlantic Ocean off Florida, but the richest and most extensive accumulations occur in large areas of the northeastern, central, and southern Pacific, where they cover 20 to 50 percent of the ocean floor.[14]

Manganese oxide nodules are usually discrete but are welded together locally to form a continuous pavement. Although they are occasionally found buried in sediment, nodules are usually surficial deposits on the seabed. Their size varies from a few

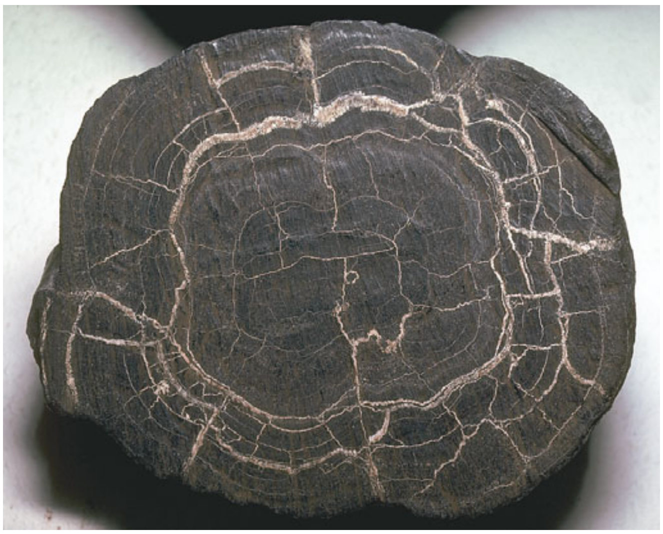


FIGURE 15.15 Manganese oxide nodule from the ocean bottom A cross section through the nodule. Notice the metallic deposits and ring structure. The diameter of the nodule is approximately 7 cm. *(William E. Ferguson)*

millimeters to a few tens of centimeters in diameter; many are marble to baseball sized. Composed primarily of concentric layers of manganese and iron oxides, mixed with a variety of other materials, each nodule formed around a nucleus of a broken nodule, a fragment of volcanic rock, or, sometimes, a fossil. The estimated rate of nodular growth is 1 to 4 mm per million years. The nodules are most abundant in those parts of the ocean where sediment accumulation is at a minimum, generally at depths of 5 to 7 km.[8,14]

The origin of the nodules is not well understood; presumably, nodules might form in several ways. The most probable theory is that they form from material weathered from the continents and transported by rivers to the oceans, where ocean currents carry the material to the deposition site in the deep-ocean basins. The minerals from which the nodules form may also derive from submarine volcanism or may be released during physical and biochemical processes and reactions that occur near the water–sediment interface during and after deposition of the sediments.[14]

Mining of manganese oxide nodules involves lifting the nodules off the bottom and up to the mining ship; this may be done by using suction or scraper equipment. Although mining of the nodules appears to be technologically feasible, production would be expensive compared to mining manganese on land. In addition, there are uncertainties concerning ownership of the nodules, and nodule mining would cause significant damage to the seafloor and local water quality, raising environmental concerns.[7]

Cobalt-Enriched Manganese Crusts. Oceanic crusts rich in cobalt and manganese are present in the mid- and southwest Pacific, on flanks of seamounts, volcanic ridges, and islands. Cobalt content varies with water depth; the maximum concentration of about 2.5 percent is found at water depths of 1 to 2.5 km. Thickness of the crust averages about 2 cm. The processes of formation are not well understood. Both the nature and the extent of the crusts, which also contain nickel, platinum, copper, and molybdenum, are being studied by U.S. Geological Survey scientists.[15]

Commercial mining of the seabed has not been seriously considered for several decades as other deposits of metals (e.g., nickel) on land at several localities has proved to be both easier to extract and thus less expensive to obtain. However, as metals become more scarce, we will probably again look to the seabed.

15.3 Environmental Impact of Mineral Development

Many scientists and other observers fear that, as population increases place more demands on mineral resources, the world will face a resource crisis. Furthermore, this crisis will come at a time when Earth may be close to the limit of its ability to absorb mineral-related pollution of air, water, land, and biological resources.[7] With this possibility in mind, we will discuss environmental impacts related to nonenergy mineral development. Development of minerals as energy sources is discussed in Chapter 16.

The environmental impact of mineral exploitation depends on factors such as mining procedures, local hydrologic conditions, climate, rock types, size of operation, topography, and many more interrelated factors. Furthermore, the impact varies with the stage of development of the resource. The exploration and testing stage involves considerably less environmental impact than the extraction and processing stages. In the United States, the time period from discovery to mine production may be several years or longer, due, in part, to environmental concerns. In countries that have less environmental control, the time from discovery to production may be much shorter. However, forgoing environmental control can lead to significant damage to the air, water, land, and ecosystems.

Impact of Mineral Exploration and Testing

Exploration and testing activities for mineral deposits vary from collecting and analyzing data gathered by remote sensing to fieldwork involving surface mapping, drilling, and gathering of geochemical and geophysical data. In general, exploration has a minimal impact on the environment, provided that care is taken in sensitive areas, such as some arid lands, marshlands, and permafrost areas (i.e., areas underlain by permanently frozen ground). Some arid lands are covered by a thin layer of pebbles over several centimeters of fine silt. The layer of pebbles, called *desert pavement*, protects the finer material from wind erosion. When the pavement is disturbed by road building or other activity, the fine silts may be eroded, impairing physical, chemical, and biological properties of the soil in the immediate environment and scarring the land for many years. In other areas, such as marshlands and

the northern tundra, wet, organically rich soils render the land sensitive to even light traffic.

Impact of Mineral Extraction and Processing

Mining and processing mineral resources are likely to have a considerable adverse impact on land, water, air, and biological resources. In addition to their direct environmental effects, these activities can initiate adverse social impacts on the environment by increasing the demand for housing and services in mining areas. These effects are part of the price we pay for the benefits of mineral consumption. It is unrealistic to expect that we can mine our resources without affecting some aspect of the local environment, but we must keep environmental degradation to a minimum. Minimizing environmental degradation can be very difficult because, while the demand for minerals continues to increase, deposits of highly concentrated minerals are decreasing. Therefore, to provide more minerals, we are developing larger operations to mine ever-poorer deposits. In the year 2000, the cumulative land use for mining on Earth was approximately 0.2 percent of the land area, or about 300,000 km^2 (115,830 mi^2).

Currently, in the United States, less than 0.3 percent, or 29,000 square km^2 (11,200 mi^2), of the total land area is dedicated to surface mines and quarries. In comparison, wilderness, wildlife, and national park lands cover approximately 500,000 km^2 (193,050 mi^2) of land. However, environmental degradation tends to extend beyond the excavation and surface plant areas of both surface and subsurface mines. Large mining operations change the topography by removing material in some areas and dumping waste in others. At best, these actions produce severe aesthetic degradation; often they produce significant environmental degradation as well. The impact of a single mining operation is a local phenomenon, but numerous local occurrences eventually constitute a larger problem.

Waste from Mines. In the United States, approximately 60 percent of the land dedicated to mining is used for mineral extraction. The remaining 40 percent is used for waste disposal. Most of the waste is overburden, the rock removed to get to the ore. This is an enormous waste-disposal problem, representing 40 percent of all of the solid waste generated in the country.[7] During the past 100 years or so, an estimated 50 billion tons of mining waste has accumulated in the United States, and the annual production of mining waste is 1 billion to 2 billion tons.[16]

Types of Mining and Their Impact. A major practical issue in mining is determining whether surface or subsurface mines should be developed in a particular area. Surface mining is more economical but has more direct environmental effects. The trend, in recent years, has moved away from subsurface mining and toward large, open-pit surface mines, such as the Bingham Canyon copper mine in Utah (Figure 15.16). This mine is one of the world's

FIGURE 15.16 Bingham Canyon copper mine near Salt Lake City, Utah Notice the large volume of mine waste, the large piles of light-colored material in the left and lower parts of the photograph. *(Michael Collier)*

largest human-made excavations, covering nearly 8 km^2 (3 mi^2) to a maximum depth of nearly 800 m (2,625 ft).

Sometimes, leaching is used as a mining technique. Leaching is the process of dissolving materials by percolating liquid through a deposit. For example, some gold deposits contain such finely disseminated gold that extraction by conventional methods is not profitable. For some of these deposits, a process known as *heap leaching* is used. A dilute cyanide solution, which is applied by sprinklers over a heap of crushed gold ore, dissolves the gold as it seeps through the ore. The gold-bearing solutions are collected in a plastic-lined pond and treated to recover the gold. Because cyanide is extremely toxic, the mining process must be carefully controlled and monitored. If an accident occurs, the process has the potential to create a serious groundwater pollution problem. Research is ongoing to develop in-place cyanide leaching to eliminate the need for removing ore from the ground. However, controlling and monitoring the leaching solution will still present a difficult problem.[17]

FIGURE 15.17 Runoff from mine tailings A zinc mine in Colorado. The white streaks (from the Eagle Mine) are mineral deposits apparently leached from tailings. Many sites such as this one have resulted from past mining practices in the United States that are not allowed today. Mining stopped in 1979 and the site has been remediated. The Eagle River near the bottom of the photograph has improved water quality. Plans are underway to develop a high-end ski resort. *(Edward A. Keller)*

Water Pollution. Water resources are vulnerable to degradation from mining. Surface drainage is often altered at mine sites, and runoff from precipitation may infiltrate waste material, leaching out trace elements and minerals. Trace elements leached from mining wastes and concentrated in water, soil, or plants may be toxic, causing diseases in people and other animals that drink the water, eat the plants, or use the soil. These potentially harmful trace elements include cadmium, cobalt, copper, lead, molybdenum, and zinc. The white streaks in Figure 15.17 are mineral deposits apparently leached from the tailings of a zinc mine in Colorado. Similar-looking deposits can cover rocks in rivers for many kilometers downstream from some mining areas. Specially constructed ponds to collect polluted runoff from mines can help, but they cannot be expected to eliminate all problems.

Groundwater may also be polluted by mining operations when waste comes into contact with slow-moving subsurface waters. Surface-water infiltration or groundwater movement through mining waste piles causes leaching of sulfide minerals that may pollute groundwater. The polluted groundwater may eventually seep into streams and pollute surface water. Groundwater problems are particularly troublesome because reclamation of polluted groundwater is very difficult and expensive.

Abandoned mines can cause serious problems. For example, subsurface mining for lead and zinc in the Tri-State area of Kansas, Missouri, and Oklahoma started in the late nineteenth century. Although it ceased in some areas in the 1960s, it has caused serious water pollution problems since then. The mines, extending to depths of 100 m (330 ft) below the water table, were pumped dry when the mines were in production. Since mining stopped, however, some mines have flooded and overflowed into nearby creeks. The water is very acidic; the sulfide minerals in the mine react with oxygen and groundwater to form sulfuric acid, a problem known as acid mine drainage (see A Closer Look: Acid Mine Drainage, in Chapter 14). The problem was so severe in the Tar Creek area of Oklahoma that, in 1982, the Environmental Protection Agency designated it as the nation's foremost hazardous waste site. Another example of acid mine drainage is in Butte, Montana, where the Berkeley Pit, a copper strip mine more than 200 m (656 ft) deep, is filling with acidic, toxic water and forming a lake (**Figure 15.18**). Pumps that kept the pit dry were turned off when the mine was closed in 1982. Some people think the lake is sure to be a tourist attraction, but to others, it is a growing threat to the environment. Wildfowl in the area have to be scared away; birds that land in the lake drink the water and die. There is increasing concern that the lake may someday leak and pollute groundwater in the Butte area.[18] Plans were developed in the 1990s to clean up the site, and they included a facility to treat contaminated water that started up in 2003.

FIGURE 15.18 Closed mine filling with toxic water The Berkeley Pit near Butte, Montana, a polluted lake in a closed copper mine. *(Calvin Larsen/Photo Researchers, Inc.)*

Acid mine drainage, in some instances, may be linked with tourism and skiing. The link results because ski resorts, such as those in mining districts of Colorado, use artificial snow makers, both early and late in the season, when natural snowfall is less likely. Making snow requires water, and, when water is withdrawn from rivers contaminated by acid mine drainage, the pollution may spread to the land when the snow melts. Ski resorts may face a no-win situation. If they withdraw acid-rich waters from streams to make snow in order to keep the ski runs open, there is a risk of contamination of the land. Choosing not to produce artificial snow may limit the use of resorts and result in financial loss. Ski resorts that make snow artificially from unpolluted water withdrawn from streams may also cause problems. Withdrawing the clean water from streams to make snow at resorts may reduce potential downstream dilution of pollutants by clean water.

As a final example of the effects of water pollution from mining areas, consider an event in Spain in the spring of 1998. The event started close to the Aznalcóllar village and mines near Seville. Acidic mining wastewater containing a toxic mixture of cadmium, zinc, lead, arsenic, cyanide, and other heavy metals, was suddenly released when a 50 m (165 ft)-wide section of an Earth dam containing the waste failed. About 7 million m^3 of toxic wastewater and mud was released downstream into the Guadiamar River, which flows into one of the most ecologically rich wetlands in Europe. Fortunately, the spill occurred where groundwater is naturally discharging to the surface of the river from the Donana aquifer rather than recharging into it. As a result, groundwater pollution may not be as extensive as it could have been if the toxic wastewater had moved into the aquifer. The potential affected area included the Donana National Park, Europe's largest nature reserve and a major tourist attraction spanning 75,000 hectares (209 mi^2) of land. The park is home to rare birds, the Iberian lynx (a wild cat), turtles,

and other species. Engineers moved quickly to construct barriers to contain the toxic spill and to collect and treat toxic mud at a site near the dam to prevent it from entering the national park. The barriers successfully kept the toxic mud from entering the park.

The toxic spill reportedly damaged fruit trees and other crops as toxic floodwaters and mud inundated the land (E. P. Martinez, personal communication, 1998). The release of the toxic chemicals produced a chain of toxicity. Dead and dying crabs, fish, and other animals, including several horses that probably drank toxic river water or were in contact with toxic mud, attracted birds and other scavengers, further spreading the toxicity through the ecosystem. To minimize the spread of toxicity by scavengers, workers used explosives and gun blasts to scare birds away from toxic areas, and hundreds of workers and volunteers collected a great number of dead eels, fish, crabs, and frogs in the days following the event.

The event occurred suddenly, and it was not entirely unexpected; for a number of years, there were early warning signs, including questions about the handling of toxic materials so close to the national park. It was also reported that the foreign company running the mine had experienced similar environmental problems in South America (J. Chacon, personal communication, 1998). The mining company, facing fines of $45 million, declared bankruptcy in 2000. By 2010, studies of the toxic pollution event concluded that while Donana National Park was apparently not significantly damaged, adjacent, upstream agricultural lands were seriously polluted and crops were lost. Recovery of the polluted soil may take several decades or more. This event raised the environmental consciousness of Spain and other parts of the world, including the mining regions of the western United States, regarding the potentially serious environmental dangers related to the management of toxic mining waste.

Air Pollution. Both extraction and processing operations have adverse effects on air quality. Smelting has released enormous quantities of pollutants into the atmosphere, including sulfur dioxide, a major constituent of acid rain and snow. Dust from mineral mines may affect air resources, despite the fact that care is often taken to reduce dust by sprinkling water on roads and other dust-producing areas.

As with water pollution, mines can contribute to air pollution problems after production has stopped. For example, toxic gases from abandoned mines in a coal-mining area in Russia have infiltrated homes by seeping into basements. There are many places in the world where mines will eventually close as they become unprofitable. Thus, planning to avoid future air and water pollution as a result of past mining activities is an important goal for people living in regions where mining has been, or is still, a widespread land use.

Impact on the Biological Environment. Physical changes in the land, soil, water, and air associated with mining directly and indirectly affect the biological environment. Direct impacts include the death of plants, animals, or people, caused by mining activity or contact with toxic soil or water from mines (see A Closer Look: Mining and Toxicity). Indirect impacts include changes in nutrient cycling; in the total mass of all living matter, called *biomass*; in species diversity; and in ecosystem stability. These indirect impacts are due to alterations in groundwater or surface-water availability or quality. The periodic or accidental discharge of pollutants through the failure of barriers, ponds, or water diversions, or through a breach of barriers during floods, earthquakes, or volcanic eruptions, also damages local ecological systems.

Social Impact. The social impact of large-scale mining results from a rapid influx of workers into areas unprepared for growth. Stress is placed on local services, including water supplies, sewage and solid-waste disposal systems, schools, and rental housing. Land use quickly shifts from open range, forest, or agriculture to urban patterns. More people also increase the stress on nearby recreation and wilderness areas, some of which may be in a fragile ecological balance. Construction activity and urbanization affect local streams through sediment pollution, reduced water quality, and increased runoff. Air quality is reduced as a result of more vehicles, dust from construction, and generation of power to run machinery and equipment.

Adverse social effects may result when miners are displaced by mine closures or automation, because towns surrounding large mines come to depend on the income of employed miners. In the old American West, mine closures produced the

A Closer Look

Mining and Toxicity

Itai-Itai Disease A serious chronic disease known as Itai-Itai has claimed many lives in Japan's Zintsu River basin. This extremely painful disease (*itai-itai* means "ouch, ouch") attacks bones, causing them to become so thin and brittle that they break easily. The disease broke out near the end of World War II, when the Japanese industrial complex was damaged and good industrial-waste disposal practices were largely ignored. Mining operations for zinc, lead, and cadmium dumped mining waste into the rivers, and farmers used the contaminated water downstream for domestic and agricultural purposes. The cause of the disease was unknown for years, but, in 1960, bones and tissues of victims were examined and found to contain large concentrations of zinc, lead, and cadmium.[19]

Measurement of heavy-metal concentrations in the Zintsu River basin showed that the water samples generally contained less than 1 part per million (ppm) cadmium and 50 ppm zinc. These metals were selectively concentrated in the river sediment and concentrated even more highly in plants. This increase in concentration from water to sediment to plants is an example of biomagnification. One set of data for five samples shows an average of 6 ppm cadmium in polluted soils. In plant roots, the average was 1,250 ppm, and, in the harvested rice, it was 125 ppm. Subsequent experiments showed that rats fed a diet containing 100 parts per million cadmium lost about 3 percent of their total bone tissue, and rats fed a diet containing 30 ppm cadmium, 300 ppm zinc, 150 ppm lead, and 150 ppm copper lost an equivalent of about 33 percent of their total bone tissue.[20]

Although measurements of heavy-metal concentrations in the water, soil, and plants of the Zintsu River basin produce somewhat variable results, the general tendency is clear: Scientists are fairly certain that heavy metals, especially cadmium, in concentrations of a few parts per million in the soil and rice, produce Itai-Itai disease.[20]

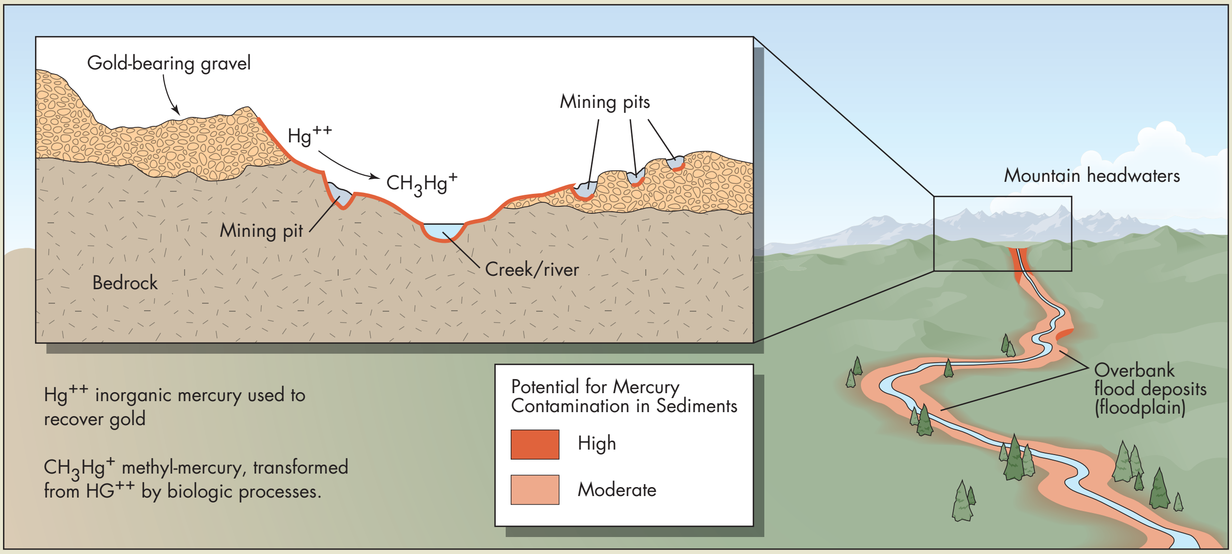
Mercury and Gold Mining
Mercury has been used in gold mining since Roman times, several thousand years ago. A native metal in its liquid state, mercury is useful in gold mining because the gold particles cling to the liquid metal, making recovery of the gold easier. In the United States during the gold rush in California, approximately 1.14 billion m^3 (1.5 billion yd^3) of gold-bearing gravels were processed by hydraulic mining from the 1850s to the 1880s. During that period, mercury was used to help recover the gold, and it is estimated that about 4,500 metric tons of mercury was lost into the environment. Much of that mercury is still working its way through the rivers and floodplains from the mining areas in the Sierra Nevada to the San Francisco Bay area. There is concern about this mercury because it is a toxic metal that, upon exposure, may damage brain cells, resulting in neurological and nervous system disease that includes fatigue and numbness of arms and legs.[21]

The major environmental issues associated with mercury toxicity in California and other mining areas include:

- Hot spots of mercury contamination at mining sites
- Contamination of the sediment with mercury and its transport down streams and rivers
- Bioaccumulation of mercury from water to sediment to plants, animals, and people
- Health issues resulting from exposure of mercury to people and other animals

Pathways of mercury-contaminated sediment from a gold mining region are shown in **Figure 15.Ca**. Notice that, initially, inorganic mercury is used to recover gold, but, as the mercury works through the environment, it is transformed by biologic processes to methyl mercury, which is the most toxic form of mercury. Mercury toxicity and potential for contamination in sediments is highest in the mining region, but problems may persist at many kilometers downstream as a result of transport of the sediment with attached mercury.

The price of gold has tripled since 2001 and, as a result, gold mines are being developed in many parts of the world, including Indonesia, South America, and Africa, where millions of poor miners are eking out a living by extracting gold from the near-surface environment, generally by panning (**Figure 15.Cb**). About 500 tons per year of mercury is believed to be used in the mining, and millions of miners and their families are being exposed to the toxic effects of mercury. In one region



(a)

(b)

FIGURE 15.C Mercury and gold mining (a) Pathways of mercury contamination in sediment from mining areas to downstream by way of runoff and rivers. *(Modified from U.S.G.S.)* (b) Panning for gold and using mercury to assist recovery. *(Indonesia AP photo, Dita Alangkara)*

alone, on the island of Borneo in Indonesia, large areas of tropical forest have been stripped bare and mined, leaving behind a wasteland with contaminated ponds containing mercury. The United States and the European Union have exported large amounts of mercury in recent years to countries with gold mining. Recently, legislation in the United States has been introduced to banish or reduce such exports, particularly to countries where people may use mercury for mining without proper safety standards.

well-known ghost towns. Today, the price of coal and other minerals directly affects the lives of many small towns, especially in the Appalachian Mountains region of the United States, where coal mine closures have taken a heavy toll. These mine closings result, in part, from both lower prices for coal and rising mining costs.

One of the reasons for the rising costs of mining is increased environmental regulation of the mining industry. The abuse of both the miners and the land mined led to the establishment of unions and mining policies. Regulations have helped make mining safer and have facilitated land reclamation. Some mining companies, however, believe the regulations are not flexible enough, and there is some truth to their arguments. For example, if the original hills have been leveled, some areas could be reclaimed for use as farmland after mining. Environmental regulation, however, may require that the land be restored to its original hilly state, even though hills make inferior farmland.

Minimizing the Impact of Mineral Development. Minimizing potential environmental impacts of mineral development requires examination of the entire cycle of mineral use, from exploration to extraction, refining, product production, and waste management. Technologically developed countries are making a good deal of progress in reversing the environmental damage done by mineral mining in the past and in minimizing the effects of new extraction and processing operations. It is the responsibility of developed countries to transfer this knowledge to the developing countries where much of the mining is taking place. Environmental laws regulate emissions and waste disposal and mandate restoration measures following mining operations. In addition, innovative technologies, particularly biotechnology, are providing more environmentally friendly ways of mining.

Environmental Regulation. Most of the serious environmental degradation associated with mining in more developed countries is a relic of past practices that are now forbidden or restricted by environmental laws. Another example of severe environmental degradation occurred in the Sudbury, Ontario, area. A century of smelting nickel ore in the area produced an area of barren land of approximately 100 km^2 (40 mi^2). Another 350 km^2 (135 mi^2) of land was extensively damaged by air pollutants from the smelters (**Figure 15.19**). The deposition of mercury, arsenic, and cadmium, among other metals, caused devastating effects on the land, water, and biological resources

FIGURE 15.19 Impact of smelters Barren land near Lake St. Charles, Sudbury, Ontario, one of the largest sources of acid rain in North America. Vegetation is killed by acid rain and deposition of toxic heavy metals, resulting from emissions from smelters. Tall stacks from the smelters are just visible on the horizon. Considerable vegetation has been restored since this photograph. *(Bill Brooks/Masterfile Corporation)*

A Closer Look

Homestake Mine, South Dakota

The Homestake Gold Mine in South Dakota, which closed in 2001, after 125 years of mining, provides an important example of the recent use of biotechnology to clean up an environment degraded by mining activity. The objective of the Homestake study is to test the use of bacterial biooxidation to convert contaminants in water to substances that are environmentally safe.[23]

The mining operation at Homestake discharges water from the gold mine to a nearby trout stream, and the untreated wastewater contains cyanide in concentrations harmful to the trout. The treatment process developed at the Homestake mine uses bacteria that have a natural capacity to oxidize the cyanide into harmless nitrates.[22] The bacteria are collected from mine-tailing ponds and cultured to allow biological activity at higher cyanide concentrations. They are then colonized on special rotating surfaces, through which the contaminated water flows before being discharged to the stream. The bacteria also extract precious metals from the wastewater that can be recovered by further processing.[22] The system at Homestake has reduced the level of cyanide in the wastewater from about 10 parts per million to less than 0.2 parts per million, which is below the level required by water-quality standards for discharge into trout streams. Because the process of reducing the cyanide produces excess ammonia in the water, a secondary bacteria treatment was designed that converts the ammonia to nitrate compounds, so that the discharged water now meets stream-water quality criteria.[23]

in the vicinity. Emissions from the smelters also contained tremendous quantities of sulfur dioxide, providing a major source of acid precipitation.[7]

Today, in the United States, smelters must adhere to air-quality emissions standards of the Clean Air Act. As a result, smelters in the United States recover almost all of the sulfur dioxide from their emissions. Canada has enacted similar clean-air legislation. Smelters in the Sudbury area have reduced their emissions of sulfur dioxide by about 50 percent, and additional reductions are slated for the future. As a result of the decrease in the pollutants from the smelters, there has been some natural recovery of the vegetation. This has been augmented by planting trees and adding lime to lakes, to help neutralize acids. These restoration measures, along with natural recovery, have resulted in revegetation of approximately 40 percent of the barren ground that surrounded the smelters.[7]

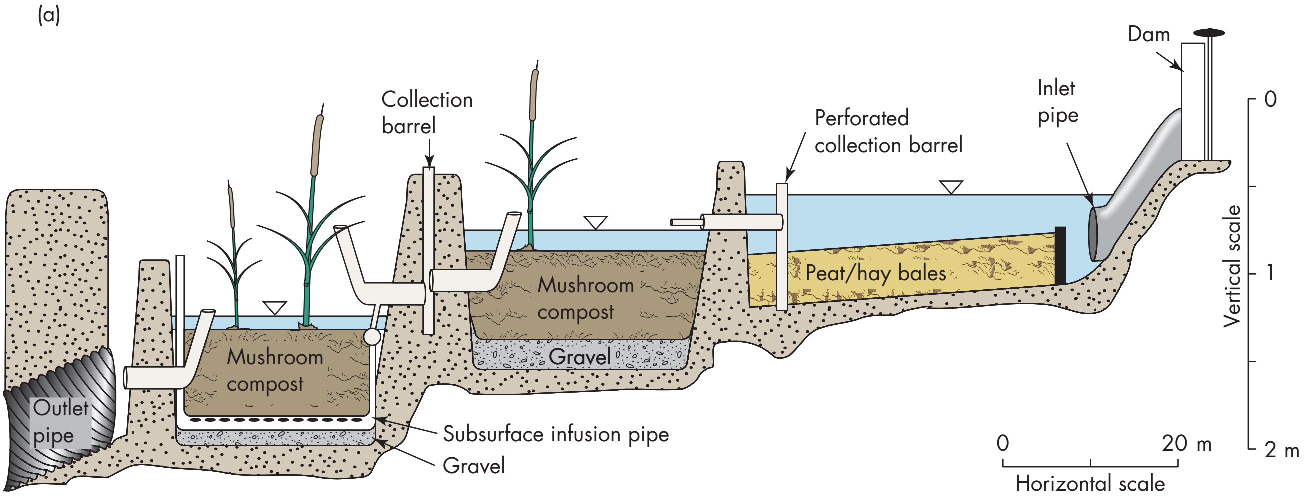
After mining activities have ceased, land reclamation, consisting of preparing the land for future uses, is necessary if the mining has had detrimental effects and if the land is to be used for other purposes. Reclamation of land used for mining is required by law today, and approximately 50 percent of the land utilized by the mining industry in the United States has been reclaimed. Methods of mine reclamation will be discussed in Chapter 16, when we consider the impact of coal mining on the environment.

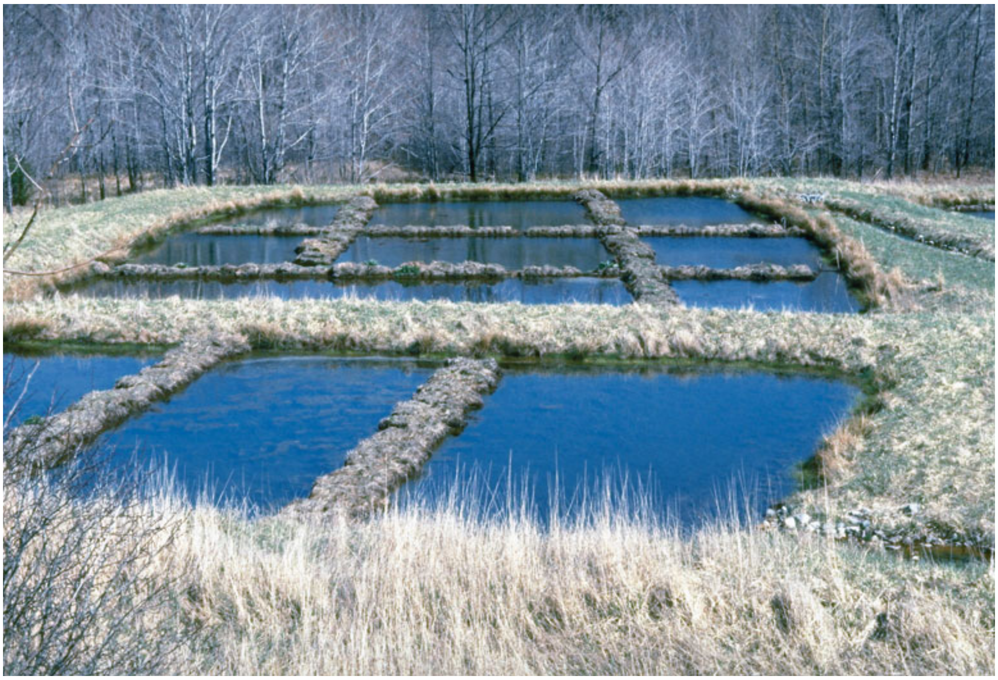
Biotechnology. Several biological processes used for metal extraction and processing are likely to have important economic and environmental consequences. **Biotechnology**, using processes such as biooxidation, bioleaching, biosorption, and genetic engineering of microbes, has enormous potential for both extracting metals and minimizing environmental degradation (see A Closer Look: Homestake Mine, South Dakota). Biotechnology is still in its infancy, and its potential uses are just beginning to be realized by the mining and metals industries.[22,23]

One promising biotechnology is bioassisted leaching, or bioleaching, which uses microorganisms to recover metals. In this technique, bacteria oxidize crushed gold ore in a tank, releasing finely disseminated gold that can then be treated by cyanide leaching. Although the cyanide is recycled during mining, it is very toxic and can contaminate groundwater resources if it is accidentally released into the environment. A commercial plant in Nevada was

constructed to produce 50,000 troy ounces (a traditional unit of measurement for gold) of gold per year by bioassisted leaching. From both economic and environmental viewpoints, this method is an attractive alternative to the cyanide-leaching process for gold extraction.[22]

Biotechnology developed and tested by the U.S. Bureau of Mines is being used to treat acid mine drainage. Constructed or engineered wetlands at several hundred sites have utilized acid-tolerant plants to remove metals and neutralize acid by biological activity (**Figure 15.20**). Both oxidizing and sulfate-reducing bacteria play an important role in the wetlands. Research is ongoing to develop an improved wetland design that requires little maintenance.[22]





(b)

FIGURE 15.20 Biotechnology and mining waste (a) Idealized diagram of wetlands constructed to use biotechnology for environmental cleanup of wastewater from mines. The plan calls for several shallow ponds lined with compost, topsoil, or crushed limestone. The plants are cattails. Bacteria are living in the compost at the bottom of the ponds. (b) Photograph of artificially constructed wetlands. *(From U.S. Bureau of Mines, Pittsburgh Research Center)*

In summary, minimization of environmental effects associated with mineral development may take several paths:

- *Environmental regulations that address problems such as sediment, air, and water pollution resulting from all aspects of the mineral cycle.* Additional regulations may address reclamation of land used for mining. (See the opening Case History about a mine near Golden, Colorado, that was transformed into a golf course.)
- *Onsite and offsite treatment of waste.* Minimizing onsite and offsite mining problems by controlling sediment, water, and air pollution through good engineering and conservation practices is a significant goal.
- *Practicing the three Rs of waste management.* That is, reduce the amount of waste produced; reuse materials in the waste stream as much as possible; and maximize recycling opportunities.

15.4 Recycling Mineral Resources

A diagram of the mineral resources cycle reveals that many components of the cycle are connected to waste disposal (**Figure 15.21**). In fact, the primary environmental impacts of mineral resource utilization are related to its waste products. Wastes produce pollutants that may be toxic to humans, are dangerous to natural ecosystems and the biosphere, are aesthetically undesirable, and may degrade air, water, and soil. Waste and other minerals that are not recycled also deplete nonrenewable mineral resources, with no offsetting benefits for human society. Recycling of resources is one way to reduce these wastes.

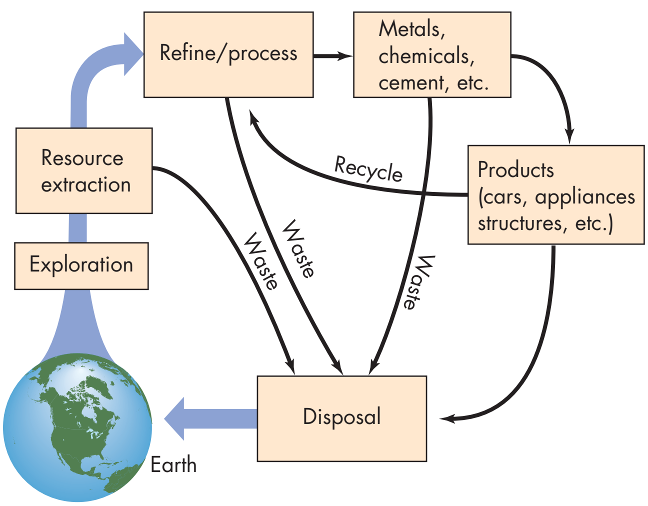


FIGURE 15.21 Waste is generated in many parts of a mineral cycle Simplified flowchart of the mineral resources cycle.

Waste from some parts of the mineral cycle may be referred to as *ore* because it contains materials that might be recycled and used again to provide energy or useful products.[24,25] The notion of reusing waste materials is not new, and such metals as iron, aluminum, copper, and lead have been recycled for many years. For example, in 2006, the total value of recycled steel in the United States was about $18.5 billion. The value of recycled steel in 2009 was about $13.5 billion (a decline of over 25 percent from 2006), reflecting economic decline due to recession. Recycling of iron and steel amounted to approximately 50 percent. Iron and steel are recycled in large volumes for three reasons[26]: (1) The market for iron and steel is huge, and, as a result, there is a large scrap collection and processing industry; (2) an enormous economic burden would result if recycling was not done; and (3) significant environmental impacts related to disposal of over 50 million tons of iron and steel would result if we did not recycle.

Other metals that are recycled in large quantities, in terms of the total metal used and their value, are lead (73 percent), aluminum (43 percent), copper (32 percent), nickel (43 percent), and titanium (47 percent). Recycling aluminum reduces our need to import raw aluminum ore and saves approximately 95 percent of the energy required to produce new aluminum from bauxite. It is estimated that each ton of recycled steel saves 1,136 kg (2,500 lb) of iron ore, 455 kg (1,000 lb) of coal, and 18 kg (40 lb) of limestone. In addition, only one-third as much energy is required to produce steel from recycled scrap as from native ore. The metal from almost all of the millions of automobiles that are discarded annually in the United States is recycled.[27]

15.5 Minerals and Sustainability

Sustainable development and mineral use do not appear to be compatible. Sustainability is a long-term concept that includes finding ways to provide future

generations a fair share of Earth's resources, and over time, nonrenewable mineral resources are consumed. However, it may be possible to find solutions to nonrenewable mineral resource use that meet the spirit, if not the letter, of sustainability. This is possible because, often, it is not a mineral we need so much but the uses for that mineral. For example, we mine copper to use it in wires to transmit electricity or electronic pulses, and it's the properties of copper, not the metal itself, that we desire. For telephone wires, we can use glass fiber cables, eliminating the need for copper. Similarly, digital cameras have eliminated the need for film development that uses silver. The photography industry is not interested in silver but, rather, the specific function of silver in photography. Therefore, it is possible to compensate for a nonrenewable mineral by finding new, innovative ways to do things. We are also learning that we may use raw mineral materials more efficiently. For example, the Eiffel Tower could be constructed today with one-fourth of the amount of steel used when it was built in the late 1800s.[28]

Finding substitutes or ways to use nonrenewable resources more efficiently usually takes several decades of research and development. The time available for finding a solution to the depletion of a nonrenewable mineral is determined using the R to C ratio (R ÷ C), where R is the known reserve and C is the rate of consumption. However, the size of a reserve is not a constant quantity through time because it changes with technology and economics. Therefore, the R to C ratio is not the time a reserve will last at the present rate of consumption. For example, during the past 50 years, R to C ratios for metals such as zinc and copper have fluctuated at about 30 years, and during that time, consumption of the metals increased by about three times. This was possible because we discovered new deposits of the metals. The ratio does provide a view of how scarce a particular mineral resource may be. Metals with relatively small ratios are viewed as being in short supply, and it is those resources for which we need to find substitutes.[28]

In summary, to reconcile sustainable development with the use of nonrenewable mineral resources, we need to find ways to more wisely use resources. This includes developing more efficient ways of exploring for and mining resources, using available resources, recycling, and applying human ingenuity to find substitutes for minerals in short supply.

Making The Connection

Linking the Opening Case History About Mine Reclamation in Colorado to the Fundamental Concepts

Consider and discuss the following questions:

1. How is future population increase in the Denver area linked to mining of resources such as clay and gravel? Can the case history provide guidance for future sequential land use where one use (e.g., mining) leads to another (e.g., golf course)?
2. How is the concept of sustainability linked to the history of the clay mine?
3. How do science and values link to how the mine in the opening case was developed, how clay was extracted, and how the land was reclaimed?
4. How is the reclamation linked to geologic hazards and their minimization?

Summary

Availability of mineral resources is one measure of the wealth of a society. Modern technological civilization, as we know it, would not be possible without exploitation of these resources. However, we cannot maintain exponential population growth on a finite resource base. Because of slow-moving geologic processes, mineral

deposits must be considered nonrenewable resources.

A mineral resource is a concentration of a naturally occurring Earth material in a form that makes extraction currently or potentially feasible. A mineral reserve is that portion of a mineral resource that is currently available, legally and economically, for extraction. It is important to remember that not all resources are reserves. Unless discovered and captured, resources cannot be used to solve present shortages.

Mineral resources may be classified according to their use as metals, building materials, minerals for the chemical industry, and minerals for agriculture. Nonmetallic minerals are consumed at much greater rates than any metal except iron. When a mineral becomes scarce, the choices are to find more sources, recycle what has already been obtained, find a substitute, use less, or do without. The United States and other affluent nations have insufficient domestic supplies of many mineral resources for current use and must supplement them by imports from other countries. As these countries industrialize and develop, the imports may be more difficult to obtain, and affluent countries may have to find substitutes for some minerals or use a smaller portion of the world's annual production. These adjustments are already occurring in the United States, where there has been a reduction in per capita nonfuel mineral consumption since the 1980s.

The geology of mineral resources is complex and intimately related to various aspects of the rock, tectonic, and hydrologic cycles. Mineral resources are generally extracted from ores, the name given to naturally occurring anomalously high concentrations of Earth materials that can be profitably extracted. To be classified as an ore, a mineral-bearing deposit must have a specific concentration factor, which is the ratio of the mineral's concentration in ore to its average concentration in Earth's crust. The concentration factor of a given mineral reflects both geologic and economic circumstances.

The environmental impact of mineral exploitation depends upon many factors, including mining procedures, local hydrologic conditions, climate, rock types, size of operation, topography, and many more interrelated factors. In addition, the impact varies with the stage of development of the resource. In general, mineral exploration and testing do little damage, except in particularly fragile areas. On the other hand, mineral mining may have major adverse effects on the land, water, air, and biological resources and may initiate social impacts on the environment, due to increasing demand for housing and services in mining areas.

Because the demand for mineral resources is increasing, we must strive to implement good engineering and conservation practices that will minimize both onsite and offsite problems caused by mineral development. The recent application of biotechnology to metal extraction and pollution reduction has real promise. Environmental degradation associated with mining and mineral processing in more developed countries has been significantly reduced in recent years, due to development of pollution abatement strategies and legislation to mandate improved pollution control measures and land reclamation. Such technologies and regulations often are not present in less developed countries that are striving to develop their mineral resources. It is the responsibility of the more developed countries to transfer technology, so that environmental degradation related to mining activities is minimized at the local, regional, and global levels.

Recycling of mineral resources is one way to delay or partly alleviate a crisis caused by the convergence of a rapidly rising population and a limited resource base.

Sustainable development and use of nonrenewable mineral resources need not be as incompatible as might be expected. We need to find ways to use our resources more wisely by finding substitutes, recycling, and conserving.

Key Terms

bauxite (p. 517)
biotechnology (p. 528)
concentration factor (p. 506)
contact metamorphism (p. 512)
evaporite (p. 513)
hydrothermal (p. 511)
manganese oxide nodule (p. 519)
ore (p. 506)
placer deposit (p. 513)
regional metamorphism (p. 512)
reserve (p. 504)
resource (p. 504)
salt dome (p. 514)

Review Questions

1. What is the difference between a resource and a reserve?
2. Define the term *ore*.
3. Define *concentration factor*.
4. Why do metallic ore deposits form at divergent plate boundaries?
5. What are the major types of mineral deposits, and how does each form?
6. List some of the major environmental impacts associated with mining.
7. What is the role of biotechnology in the mining industry?
8. Why do we recycle so much iron?

Critical Thinking Questions

1. Today, technological changes are coming from all directions. The increasing use of electronic mail (e-mail, Twitter, and Facebook) is leading us to a paperless society. We now have e-money, a technology that allows us to pay our bills via personal computers. Journals and newspapers we subscribe to come over the Internet, and we can print out only what we really want to keep. What is the impact of this technology on resource utilization? To answer this question, start by constructing a list of the resources from mineral sources necessary to support a paper-driven society. Then develop a plan to reduce the impact on natural resources of the transformation to a more paperless society.
2. Since we know that mineral resources are finite, there are two ways to look at our present and future use of these resources. One view is that we are headed toward a mineral crisis as the number of people on Earth increases. The other is that, as the number of people increases, the possibility for innovations increases, and we will, therefore, find ways to adjust our use of minerals to the increasing population. How could these two hypotheses be tested?
3. Biotechnology and genetic engineering are potential tools for cleaning up the environment. We discussed some examples of biotechnology in this chapter: Bacteria can be cultured to neutralize acids in effluent from mines, and artificial wetlands can be constructed in which biological processes purify water polluted by mineral processing and mining. What do you think of biotechnology and genetic engineering? How might the technology be transferred to the mineral industry in the United States and other countries?
4. Compare how principles of sustainability might be applied to mining copper, which is a finite resource, with water, which is a renewable resource.

Companion Website

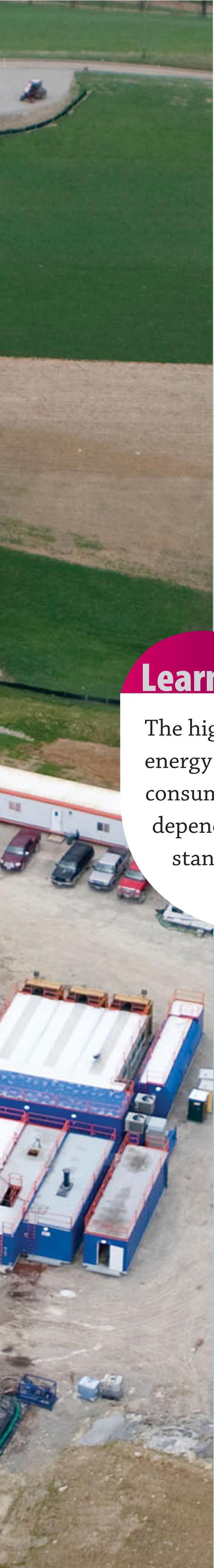
www.mygeoscienceplace.com

PEARSON mygeoscience place™

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology.*
- **Test** yourself with online quizzes.

Natural "tight gas" well being drilled. The drill site is in Washington County, Pennsylvania, in April of 2010. Pennsylvania is in an energy rush to exploit natural gas in the Marcellus Shale below the site. The large plastic lined earthen-walled pit in the lower left is for storing wastewater and mud from drilling. The pit is lined to protect the soil from contamination. *(Bloomberg/Getty Images)*



16 Energy Resources

Learning Objectives

The highly technical society in the United States consumes a disproportionate share of the total energy produced in the world. With only 5 percent of the world's population, the United States consumes approximately 20 percent of the world's total energy. How can we break our dependency on energy sources that harm the environment (e.g., coal, oil) without sacrificing our standard of living? In this chapter, we explore possible answers to this important question. The focus will be on the following learning objectives:

- **Understand the concept of peak oil and how it might impact our economic and social environment**
- **Know the general patterns of energy consumption in the United States**
- **Know the types of major fossil fuels and the environmental impact associated with their development**
- **Understand nuclear energy and its associated important environmental issues**
- **Understand geothermal energy, how it is produced, and its future as an energy source**
- **Know the main types of alternative and renewable energy and their environmental significance**
- **Know the important issues related to energy policy, particularly the concept of sustainable energy development**

Case History

Energy Transitions from Approximately 1800 to Present

The amount of fossil fuels, especially petroleum, in Earth is finite. As a result, a transition from oil will be necessary in the future. An interesting comparison to examine is an earlier energy transformation in the United States from wood in the mid-1800s to fossil fuels in the mid-1900s. The consumption of energy from 1800 to 2009 in the United States is shown in **Figure 16.1**. Notice that the peak in use of wood was approximately 1870, when coal started to be burned in a more serious way. In the mid-1800s and for a period of about 100 years, something like 95 percent of the total energy in the United States, as well as the rest of the world, came from wood as the primary source of energy. The transition to coal and, eventually, to oil and gas began in a small way, and the transition was not a smooth one. It took something like 100 years for the full transition to take place. This resulted because there were lots of things to consider, including what people were accustomed to and the driving forces behind economic and social change.[1,2]

Shortages of wood in 1812 in Philadelphia led to experiments with burning coal, and the first oil well was completed in 1858. Up to that time, the primary source of oil was whale oil. Following the use of petroleum that produced kerosene, the United States left the whale-hunting industry behind. The fossil fuels were very attractive because of their high heat value for the volume of fuel and because they were, initially, plentiful, easy to extract, and not very expensive. In other words, the transition from wood to fossil fuels was one from a rather low grade source of energy (i.e., wood) to a much higher one (i.e., coal and oil) at a lower price. Flash forward to the late twentieth and into the twenty-first centuries, and we now understand that the burning of oil will, naturally, need to be transitioned to other energy sources, such as coal, natural gas, nuclear energy, solar, and wind,

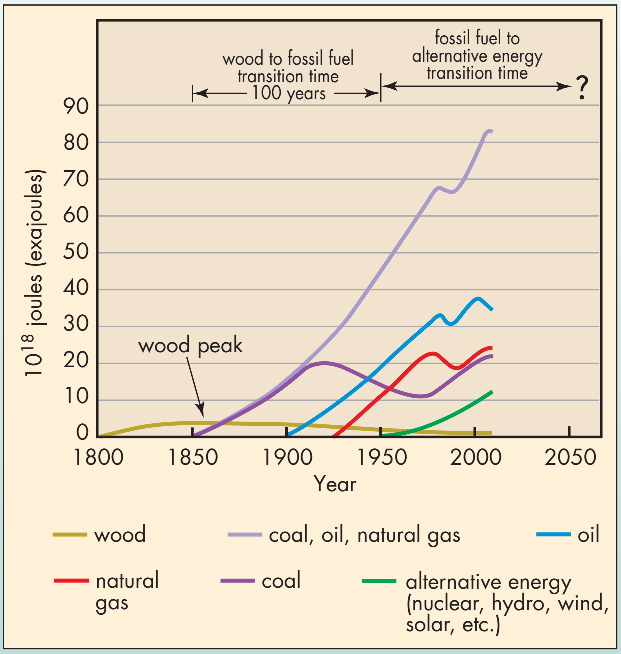


FIGURE 16.1 History of U.S. energy transformation
(Modified from Energy Information Administration. 2010. Annual Energy Review, *2009)*

16.1 Worry Over Energy Sources Is Nothing New: Energy Shocks Past and Present

Two thousand years ago, the homes of affluent Roman citizens had central heating that consumed vast amounts of wood—perhaps as much as 125 kg (275 lb) every hour. Wood was the fuel of the day, much like oil and gas in the United States today. The exhaustion of local supplies of wood produced shortages and a shock to the Roman society. To combat the shortages, the Romans had to import wood from distances as far away as 1,600 km (995 mi). As distant supplies of wood became scarce, the Romans faced a second energy shock. They turned to solar energy as an alternative, with considerable success. Ancient Romans became so efficient in the use of solar energy that they established

among others. The transition from fossil fuels to alternative sources will involve two steps: transition from oil followed by transition from coal and natural gas. The transition from oil will happen because oil will eventually (some say soon) come into short supply and be much more expensive. Sometimes, people claim that the transition can happen quickly, and you may hear statements about it being done over 20 to 30 years if we apply our best thinking, as with the project to land a person on the Moon. Using natural gas and coal for basic modes of transportation (i.e., cars, trucks, trains, and airplanes) will be difficult and will be associated with known environmental problems, such as air pollution. Using vast amounts of alternative energy sources, such as wind and solar, that are growing rapidly is technically possible (as is the use of massive amounts of coal and natural gas), but the time necessary for the transition from oil is likely to be closer to 100 years than to 30 years.

The first energy transition from wood to fossil fuels took over a century, and, during the transition, energy use in the world increased by a factor of about 20. Therefore, replacing even half of the oil consumed today by other energy sources in a few decades would require a tremendous effort; it is not impossible but not likely. The transition to alternative energy sources, such as solar and wind, to produce half of our energy consumption today would require the alternative energy sources to grow by approximately 12 times. Another potential problem with the transition is that, with this transitioning, a fuel that is often less reliable (e.g., wind doesn't blow all the time and the Sun shines only half the time) may be used to replace a more reliable source (e.g., fossil fuels). Alternative fuels also have a lower energy density with respect to amount of energy per volume or weight. The transition from oil to alternative energy (with the exception of nuclear energy) requires moving from a higher source of energy to a lower one. With respect to specific alternative energy sources (other than nuclear), it is clear that wind could make a significant contribution in the future. However, the real hope is for development of solar energy because, by itself, it could meet all of our future demands for electricity. However, the goal of turning solar energy into useful energy at a low cost has still not been achieved, and we will have to learn to deal with infrastructure problems for delivery of that energy. Today, direct production of electricity from solar sources is only about 0.1 percent of the world's energy production of electricity, which means a scaling up factor would have to be something like 1,000 times if solar were to account for all the electric energy we use on Earth. Solar energy is an attractive source, but no matter how attractive it is, it will take time to create the infrastructure, produce the energy, and transport it where it is used. Another challenge with the transition to alternative energy to supply most of the energy now produced by oil is that many of the alternatives, at this point, are not all that attractive. They do not provide new energy services (they mainly produce electricity), and they cost more than oil.[1,2] Therefore, the transition from oil will require continuing to burn other fossil fuels (i.e., coal and natural gas) until alternative sources can be ramped up. Natural gas is environmentally preferred over coal as it is much less polluting.

The transition from oil will occur (it is definitely coming). The problem is not the technology to make the transition so much as the willpower to make the transition (i.e., science and value issues). Eventually, cost will drive the transition as oil becomes more expensive, but, if we are proactive, we will begin more serious work on that transition—sooner rather than later. The fact that the use of solar and wind energy are doubling every year or two is a good sign, but the scaling up of alternative energy to provide a significant portion of what is now provided by fossil fuels will be a daunting task. However, we need to continue the research, development, and incentives and pursue alternative energies very vigorously in the coming years.[1,2]

laws to protect a person's right to his or her share of the solar energy. In some cases, it was illegal to construct a building that shaded a building next door because the shade would rob the neighbors of their share of the solar resource.[3]

During the summer of 2008, U.S. citizens were shocked by the rapid price increase of gasoline. The sharp price increase followed years of lower prices (particularly in the 1990s), due to an oil and gasoline glut. The reasons for the price increase are complex and based upon several factors: Oil-producing countries reduced production rates, there was political unrest and war in the Middle East, and the U.S. government instituted regulations that required oil producers to reduce air pollution by reformulating gasoline with additives that produce cleaner-burning fuel. These factors, as well as suspected price gouging by oil companies, resulted in shortages, and, by August 2008, crude oil cost over $100 per barrel (1 barrel is 42 gallons). By late 2008, the price had

dropped significantly from the high in the summer, and, by April 2009, the price was about \$40 per barrel (the price in 2004), and by late 2010, was back up to about \$80 per barrel. As dramatic as the price increases were, they were not the first; there had been several such oil shocks in a space of less than 30 years.

The price increase in gasoline was preceded by the "California energy crisis," with its rolling blackouts, in 2001. This crisis was a wake-up call to the entire country. The crisis resulted, in part, because, as California prospered and grew in population, demand for energy increased. California imports a large percentage of its electrical energy and failed to bring sufficient new sources of energy online. Utility companies that had been deregulated a few years before were forced to purchase emergency power from suppliers that charged as much as 900 percent more than normal. One of the state's largest power companies went bankrupt, and the governor of California initiated an investigation of illegal market control and price gouging by energy suppliers. More power plants are being constructed, but the short-range future is uncertain.

August 14, 2003, brought an energy shock to New York City and the surrounding region as a massive eight-state blackout occurred. More than 50 million people were affected. Some were trapped in elevators and electric trains underground. Power was restored to most places within 24 hours. The power failure started at a U.S. power plant and quickly cascaded to become a widespread failure. The blackout emphasized our dependence on an aging centralized power distribution system and the need for improved energy management.

The Romans' use of solar energy illustrates that energy problems are not new. As one source of energy becomes scarce, and energy shocks occur, we search for alternatives. Today, as mentioned in the opening case history about energy transformations, we fear that production of crude oil will peak in the next decade or so. Like the Romans, we will need alternatives; perhaps it will be solar energy again. Energy from local to global scale has emerged as a central economic concern, a foreign policy issue, and an environmental question.[4] How we respond to energy issues will largely define who and what we are and will become in the twenty-first century. In this chapter, we will explore present energy use, environmental effects of energy consumption, and what the future might hold in terms of establishing sustainable energy development.

16.2 Peak Oil: When Will It Occur and What Is Its Importance?

Peak oil is the term for the concept that a time will come when one-half of Earth's oil has been extracted and used. Peak oil is likely to occur sometime between 2020 and 2050.[5,6]

The United States is prosperous, and people are living longer, as a result of abundant low-cost energy in the form of crude oil. While the benefits of oil are undeniable, so also are the environmental problems associated with it, ranging from air and water pollution to global warming. We are about to learn what life is like with less, more expensive oil. The question is not *if* the peak in production of oil will come, but *when*, and what the economic and political consequences to society will be.[5]

The reality of peak oil in the United States is shown in **Figure 16.2**. U.S. oil production peaked (as predicted years earlier) in 1970, at 11.3 million barrels per day. In that year, the United States imported 3.2 million barrels per day. Imports just equaled exports by 1996. In 2009, production was about

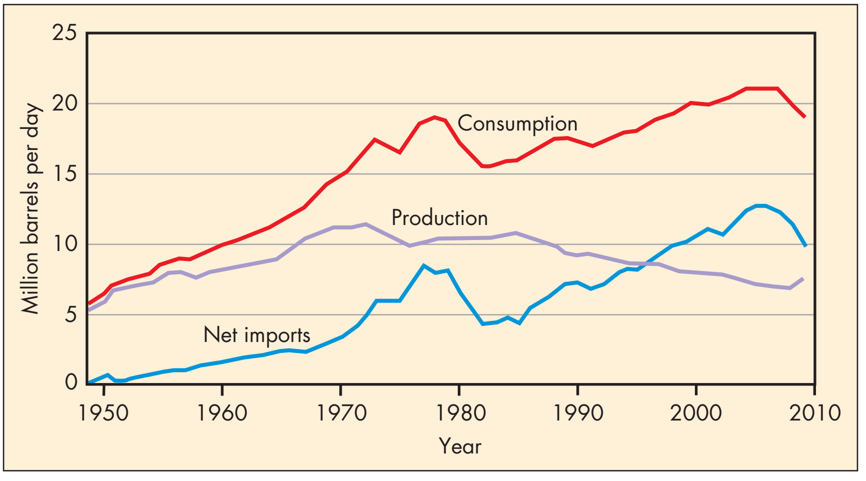


FIGURE 16.2 History of U.S. oil Production peaked in 1970; consumption matched imports by 1996; and, by 2007, imports were 1.7 times production. *(Modified from Energy Information Administration. 2010.* Annual Energy Review, 2010)

8 million barrels per day, and imports were about 10 million barrels per day.

The global history of oil, in terms of rate of discovery and consumption (**Figure 16.3**), is an important factor in peak oil. Nearly five times more oil was discovered in 1960 than was consumed. However, by 1980, the amount discovered was equivalent to the amount consumed; and, in 2000, the consumption of oil was three times the amount discovered. This trend is not sustainable. The unfortunate truth is that oil is being consumed rapidly, relative to new resources being found. In 2006, oil companies reported the largest discovery of oil ever in the United States. At 15 billion barrels, when extracted and consumed by users of the world market, it will provide about a 6-month supply of oil. If all 15 billion barrels is saved for the United States, it will be only about a 2-year supply.

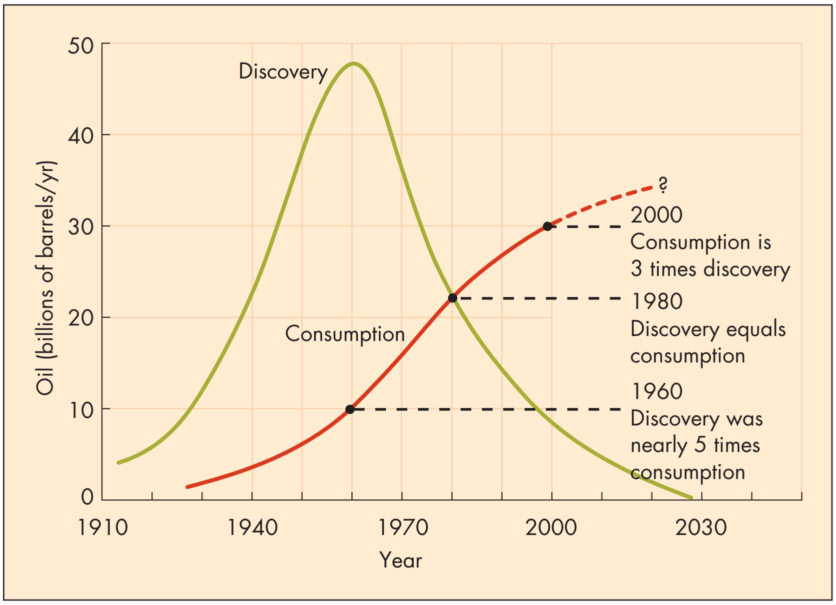


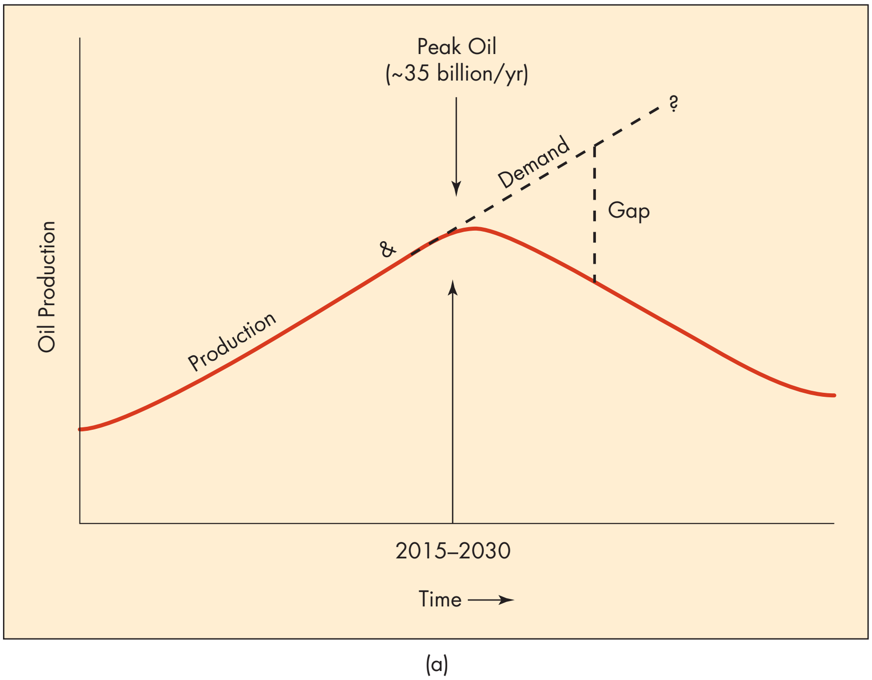
FIGURE 16.3 U.S. oil discovery and consumption Discovery of oil peaked in about 1960, and consumption exceeded discovery by 1980. *(Modified after K. Aleklett. 2006. "Oil: A bumpy road ahead,"* World Watch *19(1):10–12)*

The concept of peak oil production is shown in **Figure 16.4a**. We aren't confident about when the peak production will be because it depends, in part, on technology, conservation, and use of alternative fuels, such as ethanol (biofuel). For this discussion, let's assume it to be about 35 billion barrels per year (95 million barrels per day), and that the peak arrives sometime between 2015 and 2030. The growth rate for oil in the past year or so has been nearly flat, so increasing from the present production rate of about 31 billion barrels per year to 35 in a few decades seems reasonable. When peak production occurs and demand increases, a gap between production and demand will become evident. Figure 16.4b shows two possible scenarios. The first is a flat peak from 2004 to about 2025; production has been relatively stable, at about 82 million barrels per day. If demand is approximately 115 million barrels per day, the gap will be about 34 million barrels per day. If production increases to match demand in 2015 (scenario 2), then a gap will occur after 2015. Cost will increase as peak oil becomes a reality, and, if we haven't prepared for the peak, economic and political disruption to society are inevitable. We still have time to prepare for the eventual peak and use remaining fossil fuels to help transition to other energy sources. In the most optimistic scenario, the transition from oil to alternative fuels will not occur until we have cost-competitive choices in place.[6]

When the peak in oil production occurs, we will not run out of oil, but oil will become much more expensive. When that happens, the peak will be different from any problem we have faced in the past. Human population will increase by several billion more in coming decades, as countries with growing economies, including China and India, increase their oil consumption. China may double its import of oil in the next 5 years! As supplies tighten, the economic, social, and political ramifications of competition for oil will be enormous. Planning to conserve oil and transition to alternative energy sources will be critical in the coming decades. We cannot afford to leave the age of oil behind until alternatives are in place.

16.3 Energy Supply and Energy Demand

Nearly 90 percent of the energy consumed in the United States today is produced from coal, natural gas, and petroleum or oil. These energy resources are sometimes called **fossil fuels** because of their organic origin. These fuels are nonrenewable resources. The remaining 10 percent of energy consumed



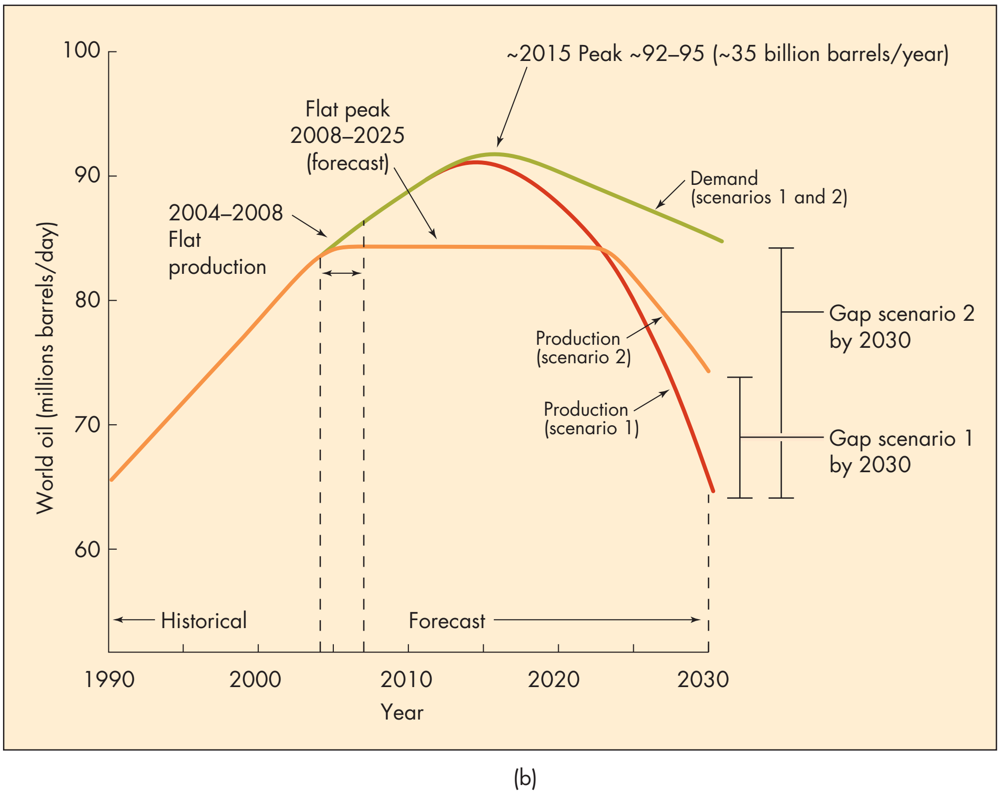


FIGURE 16.4 Peak oil (a) Idealized diagram illustrating the concept of "peak oil," when one-half of the world's oil will have been produced. When demand is greater than production, a gap (shortage) develops. This may happen between 2015 and 2030. (b) Two scenarios for peak oil: scenario 1, with a flat peak until 2025, followed by decline in production, and scenario 2, with a peak in 2015, followed by decline. *(Data from Roberts, P. 2008. Tapped Out.* National Geographic *6(213):86–91)*

originates mostly from hydropower and nuclear power. We still have huge reserves of coal, but major new sources of natural gas and petroleum are becoming scarce. In fact, we import approximately the same amount of oil that we produce, which makes us vulnerable to changing world conditions that affect the available supply of crude oil. Few new large hydropower plants can be expected, and the planning and construction of new nuclear power plants have become uncertain for a variety of reasons. More recently, alternative energy sources, such as solar power for homes, farms, and offices, are becoming economically more feasible and, thus, more common.

Changes in energy consumption in the United States are shown in **Figure 16.5**. From 1950 through 2009, there was a sharp increase in energy consumption; the rate of increase declined after the shortages in the mid-1970s to mid-1980s. The rate of energy consumption increased again during the last decade of the twentieth century, due to abundant cheap oil. Total U.S. energy consumption has increased by about 30 exajoules (EJ) since 1985 (see A Closer Look: Energy Units for an explanation of exajoules). Energy conservation policies, such as requiring new automobiles to be more fuel efficient and buildings to be better insulated, have been at least partially successful. Nevertheless, at the beginning of the twenty-first century, we remained hooked on fossil fuels. U.S. energy policy will be an important topic in the coming decades. Some topics being discussed are listed in **Table 16.1**.[4]

Projections of energy supply and demand are difficult, at best, because the technical, economic, political, and social assumptions that underlie these projections are constantly changing. It is clear, however, that we must continue to research, develop, and evaluate potential energy sources and conservation practices to ensure sufficient energy to maintain our industrial society, along with a quality environment. In the United States, space heating is the main use of energy for applications below 300°C (572°F). With these ideas in mind, we will explore some selected geologic and environmental aspects of well-known energy resources, including coal, oil, and nuclear sources, as well as potentially important sources, such as oil shale, tar sands, and geothermal resources. We will also discuss renewable energy sources, such as hydropower, wind, and solar power.

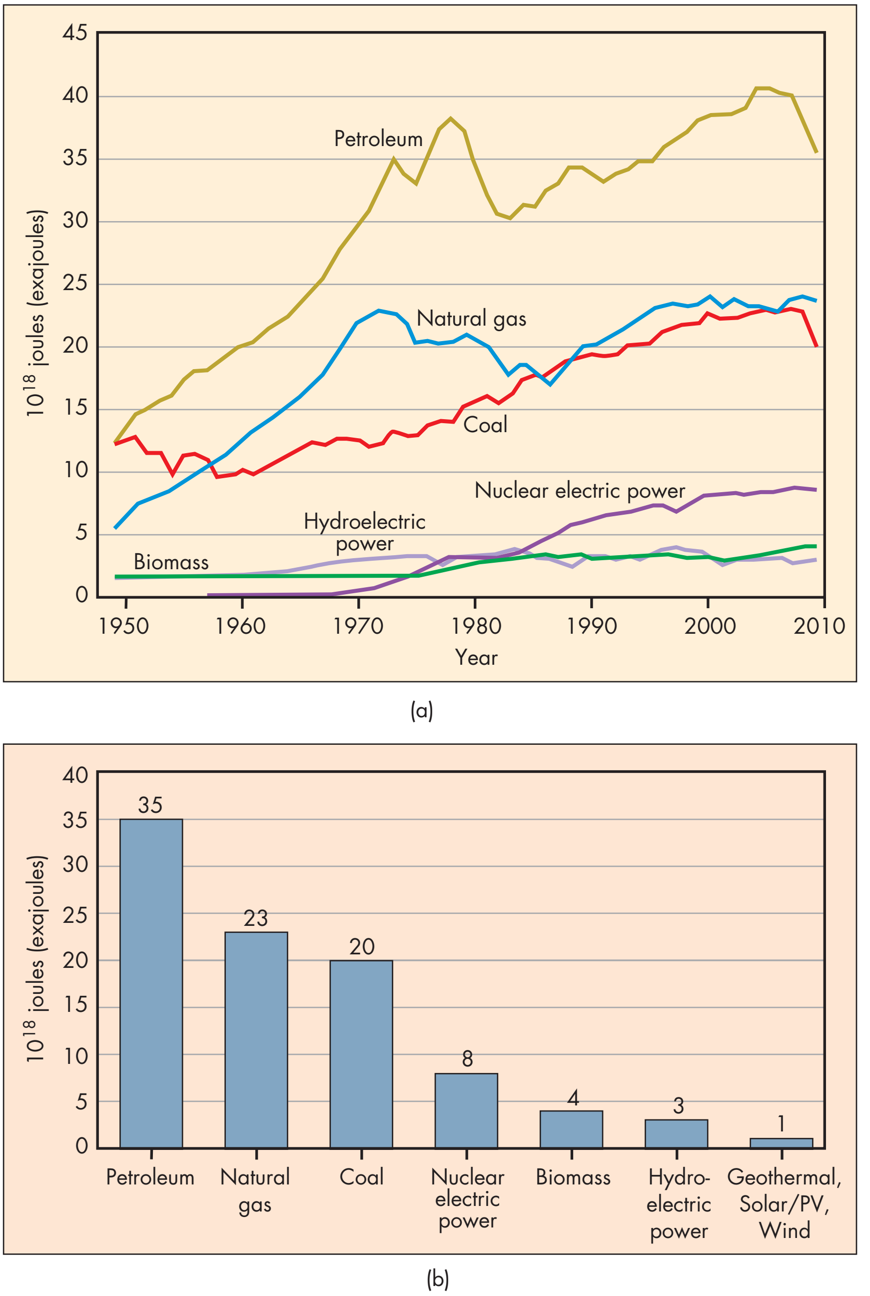


FIGURE 16.5 U.S. energy (a) U.S. energy consumption 1950–2009 by source. (b) U.S. energy consumption for 2007. *(Modified after Energy Information Administration. 2010.* Annual Energy Review, 2009*)*

16.4 Fossil Fuels

The origin of fossil fuels—coal, oil, and gas—is intimately related to the geologic cycle. These fuels are, essentially, solar energy stored in the form of organic material that has been transformed by physical and biochemical processes after burial. The United States is dependent on fossil fuels for nearly all the energy we consume. This situation is changing—slowly.

A Closer Look: Energy Units

The basic unit for energy expenditure is the joule (J). One joule is defined as a force of 1 newton applied over a distance of 1 m (3.3 ft). A newton (N) is defined as the force necessary to produce an acceleration of 1 m per second per second (m/sec^2) to a mass of 1 kg. From 1950 through 2007, total U.S. energy consumption increased from 30 to approximately 100 exajoules (EJ); 1 EJ is equal to 10^{18} J and approximately equal to 1 quad, or 10^{15} Btu. The units for power are time rates of energy or joules per second (J/sec); 1 J/sec is 1 watt (W). A large power plant produces about 1,000 megawatts (MW), which is 1 billion watts (1 gigawatt [GW]). Electrical energy is commonly sold by kilowatt-hours (kWh). This unit is 1,000 W applied over 1 hour (3,600 sec). Thus, 1 kWh is 3,600,000 J, or 3.6 MJ.

TABLE 16.1 Energy Policy: What Is Being Discussed

1. Promote conventional energy sources: Use much more natural gas, with the objective of reducing our reliance on energy from foreign countries, and use natural gas as a transition from oil.
2. Encourage alternative energy: Provide support or subsidies for wind energy and other alternative energy sources, such as solar, geothermal, hydrogen, and biofuels (ethanol and biodiesel). Increase the amount of biofuel (ethanol) mixed with gasoline sold in the United States.
3. Provide for energy infrastructure: Ensure that electricity is received over dependable, modern infrastructure.
4. Promote conservation measures: Set higher efficiency standards for federal buildings and for household products. Require that what is now waste heat from power generation and industrial processes be used to produce electricity or other products. Recommend fuel-efficiency standards for cars, trucks, and SUVs. Give new tax credits for installing energy-efficient windows and appliances in homes. Provide a tax credit for purchasing a fuel-efficient hybrid or clean-diesel vehicle. Develop smart electric grids in homes, communities, and regions to optimally manage energy use with the object of conserving energy.
5. Seriously consider nuclear power: Recognize that nuclear power plants can generate large amounts of electricity without emitting air pollution or greenhouse gases.
6. Promote research: Develop alternative energy sources; find innovative ways to improve coal plants and to help construct cleaner coal plants; determine how to safely tap into the vast amounts of oil trapped in oil shale and tar sands; and develop pollution-free automobiles.

The environmental disruption associated with the exploration and development of fossil fuels must be weighed against the benefits gained from the energy, but it is not an either–or proposition. Good conservation practices, combined with pollution control and reclamation, can help minimize the environmental disruption associated with fossil fuels.

Coal

Coal is one of the major fossil fuels. Burning coal accounts for about 20 percent of the total energy consumption in the United States. As we shall discuss, the environmental costs of coal consumption are significant.

Geology of Coal. Like the other fossil fuels, coal is composed of organic materials that have escaped oxidation in the carbon cycle. Essentially, coal is the altered residue of plants that flourished in ancient freshwater or brackish swamps, typically found in estuaries, coastal lagoons, and low-lying coastal plains or deltas.

Coal-forming processes begin in swamps rich in plant life, where water-saturated soils exclude much of the oxygen normally present in soil (**Figure 16.6**). The plants partially decompose in this oxygen-deficient environment and slowly accumulate to form a thick layer of material called *peat*. The swamps and accumulations of peat may then be inundated by a prolonged, slow rise in sea level, caused either by an actual rise of sea level or by sinking of the land; sediments, such as sand, silt, clay, and carbonate-rich material, are then deposited on the peat. As more and more sediment is deposited, water and organic gases, or volatiles, are squeezed out, and the percentage of carbon increases in the compressed peat. As this process continues, the peat is eventually transformed to coal. Because there are often several layers of coal in the same area, scientists believe that the sea level may have alternately risen and fallen, allowing development and then drowning of peat swamps.[7]

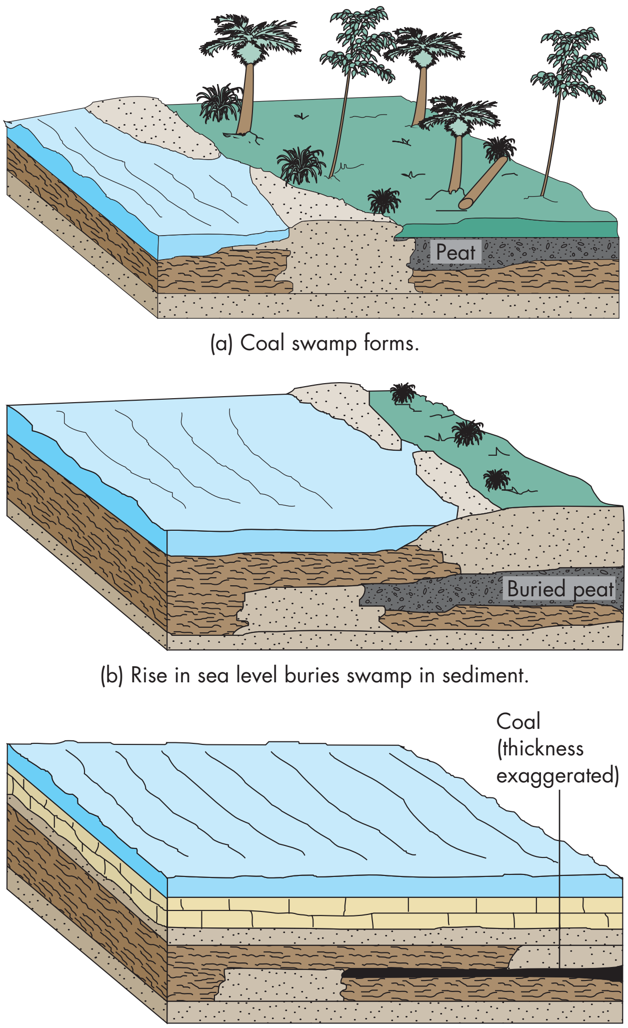


FIGURE 16.6 How coal forms The processes that convert buried plant debris, or peat, into coal. Considerable lengths of geologic time must elapse before the transformation is complete.

Classification and Distribution of Coal. Coal is commonly classified according to type and sulfur content. The type is generally based on both the percentage of carbon in the coal and its heat value on combustion. The percentage of carbon in coal increases among the four types found in Earth, from lignite to subbituminous to bituminous to anthracite (**Figure 16.7**). Figure 16.7 also shows that heat content is maximum in bituminous coal, which has relatively few volatiles, such as oxygen, hydrogen, and nitrogen, and low moisture content. Heat content is minimum in lignite, which has a high moisture content. The distribution of the common types of coals in the contiguous United States is shown in **Figure 16.8a**. The distribution of world coal reserves, which amount to about 1,000 billion metric tons, is shown in Figure 16.8b. The

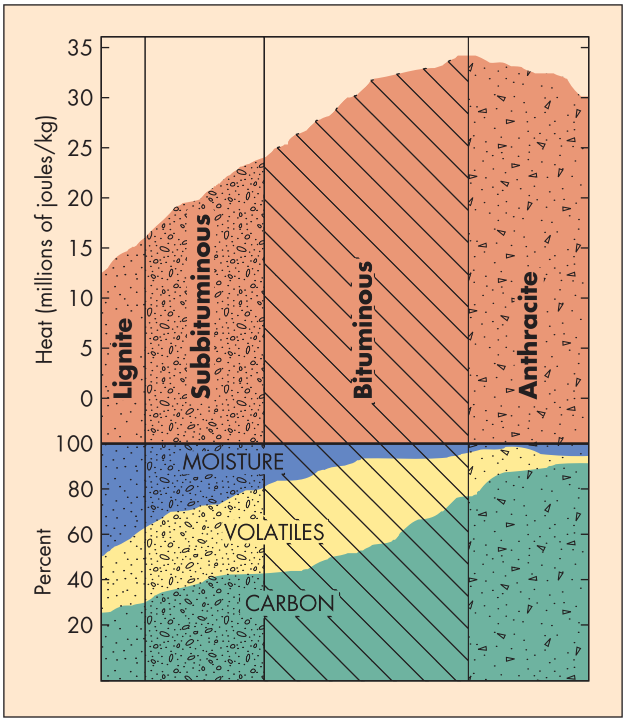


FIGURE 16.7 Types of coal Generalized classification of types of coal, based on their relative percent content of moisture, volatiles, and carbon. The heat values of the different types of coal are also shown. *(After Brobst, D. A., and Pratt, W. P., eds. 1973. U.S. Geological Survey Professional Paper 820)*

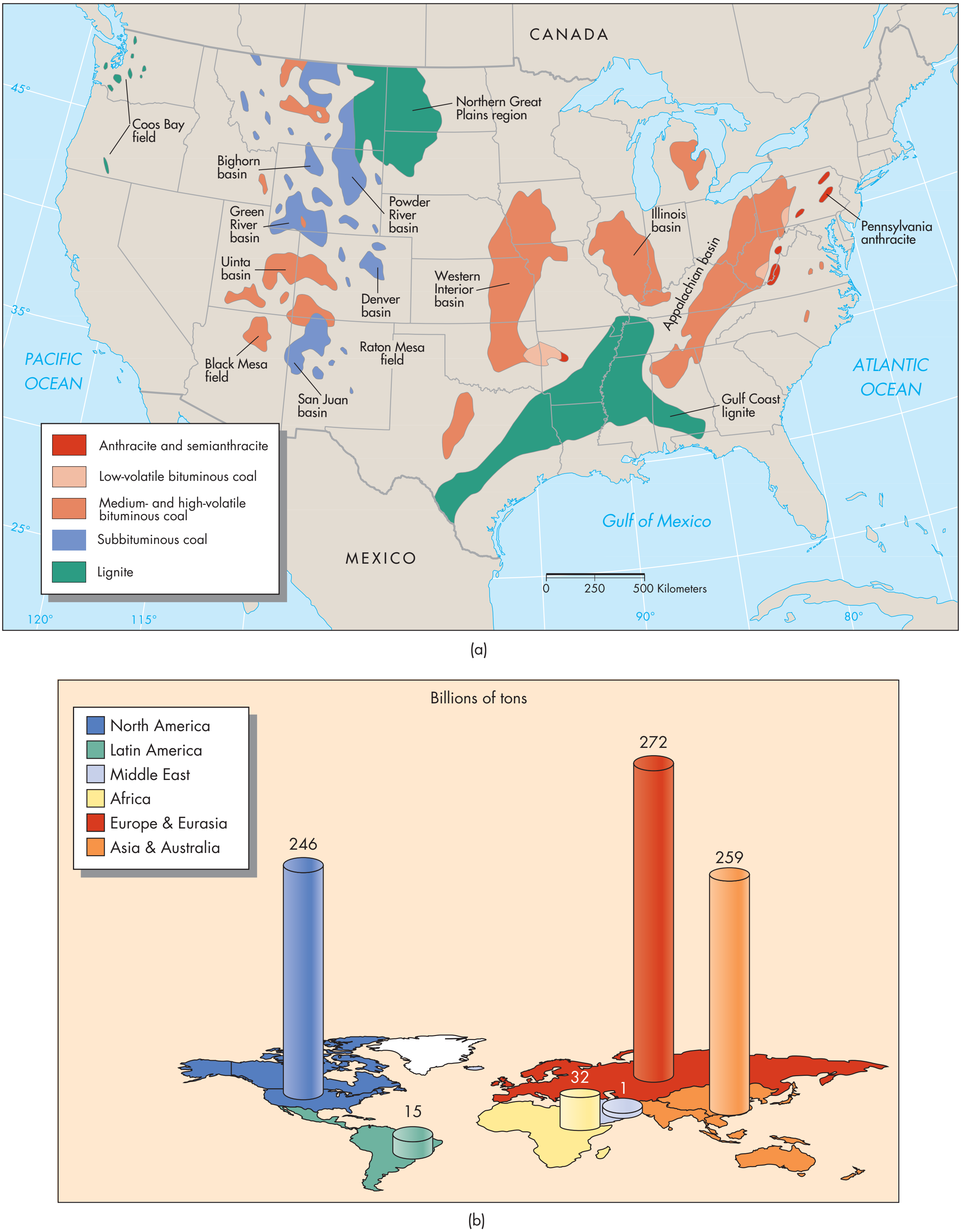


FIGURE 16.8 World coal reserves (a) Coal areas of the contiguous United States. *(Carbini, S., and Schweinfurth, S. P. 1986. U.S. Geological Survey Circular 979)* For a more detailed map, see Coal Fields of the Conterminous United States US65 Open File Report of 96–92 (1996). (b) World coal reserves (billions of metric tons) in 2009. The United States has about 25 percent of the total reserves. Unlike oil, coal reserves are more evenly distributed around the world. *(British Petroleum Company. 2010.* BP Statistical Review of World Energy*)*

United States has about 25 percent of these reserves. The annual world consumption of about 5 billion tons suggests that, at the present rate of consumption, known reserves are sufficient for over 200 years.[8] It is likely, however, that in countries undergoing intensive industrialization, such as China, reserves may be depleted sooner.

The sulfur content of coal may generally be classified as low (0 to 0.60 percent), medium (0.61–1.67 percent), or high (greater than 1.67 percent). All other factors being equal, the use of low-sulfur coal as a fuel for power plants releases less sulfur dioxide (SO_2) and causes the least air pollution. Most coal in the United States is the low-sulfur variety; however, by far the most common low-sulfur coal is a relatively low-grade, subbituminous variety found west of the Mississippi River (**Table 16.2**).[9] To avoid air pollution, thermal electric power plants on the highly populated East Coast must continue to either treat local coal to lower its sulfur content before burning or capture the sulfur after burning. Treatment increases the cost of thermal electric power, but it may be more economical than transporting low-sulfur coal from west of the Mississippi River.

Impact of Coal Mining. Most of the coal mining in the United States is done by open-pit mining, or *strip mining*. Strip mining began in the late nineteenth century and has steadily increased, whereas production from underground mines has stabilized. As a result, most coal today is obtained from surface mines west of the Mississippi River. In recent years, strip mining in the Appalachians, using a technique known as *mountain-top removal*, has become more common. Coal is mined from tops of mountains, and the waste rock from mining is placed in valleys, where coal sludge produced from processing the coal is stored behind coal-waste sludge dams. Strip mining is, in many cases, technologically and economically more advantageous than underground mining. The increased demand for coal will lead to more and larger strip mines to extract the estimated 40 billion metric tons of coal reserves that are now accessible to surface mining techniques. In addition, approximately another 90 billion metric tons of coal within 50 m (165 ft) of the surface is potentially available for stripping, if needs demand it. To put this in perspective, consider that the annual U.S. production is about 1 billion metric tons, and the world production is about 5 billion metric tons per year.[8]

The impact of large strip mines varies by region, depending on topography, climate, and, most importantly, reclamation practices. In humid areas with abundant rainfall, mine drainage of acid water is a serious problem (**Figure 16.9**). Surface water infiltrates the spoil banks (i.e., the material left after the coal or other minerals have been removed), reacts with sulfide minerals such as pyrite (FeS_2), and produces sulfuric acid. The sulfuric acid then runs into and pollutes streams and groundwater resources. Although acid water also drains from underground mines, road cuts, and areas where coal and pyrite are abundant, the problem is magnified when large areas of disturbed material remain exposed to surface waters. Acid drainage can be minimized through proper use of water diversion practices that

TABLE 16.2 U.S. Coal Classified by Sulfur Content

Region[a]	Sulfur Content Categories[b]		
	0 to 0.6% (Low Sulfur)	1.61 to 1.67% (Medium Sulfur)	greater than 1.67% (High Sulfur)
Appalachia	16.0	26.6	26.0
Interior	0.7	15.3	66.4
West	83.3	59.2	7.6
U.S. Total	100.0	100.0	100.0

[a] **Appalachia**—Alabama, Georgia, eastern Kentucky, Maryland, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia. **Interior**—Arkansas, Illinois, Indiana, Iowa, Kansas, western Kentucky, Louisiana, Missouri, Oklahoma, Texas. **West**—Alaska, Arizona, Colorado, Idaho, Montana, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, Wyoming.

[b] Assumes that 100 percent of the sulfur in the coal is converted to sulfur dioxide and none is retained in the ash.

Source: Energy Information Administration. 1993. U. S. Coal Reserves: An update by heat and sulfur content. DOE/EIA-0529(92).

FIGURE 16.9 Acid mine drainage Acid-rich water draining from an exposed coal seam is polluting this stream in Ohio. *(Kent & Donna Dannen/Photo Researchers, Inc.)*

collect surface runoff and groundwater before they enter the mined area and divert them around the potentially polluting materials. This practice reduces erosion, pollution, and water-treatment cost.[10]

In arid and semiarid regions, water problems associated with mining are not as pronounced as in wetter regions. However, arid land may be more sensitive to mining activities, such as exploration and road building. In some arid areas, the land is so sensitive that even tire tracks across the land survive for years. Soils are often thin, water is scarce, and reclamation work is difficult.

All methods of strip mining have the potential to pollute, but reclamation practices can minimize the environmental damage of strip mining (**Figure 16.10**). Reclamation begins with segregation of the soil and *overburden*, the rock above the coal. After mining, the topsoil that was removed is replaced. This method is widely used, and it is a successful way to minimize water pollution when combined with regrading and revegetation.[10]

FIGURE 16.10 Mining coal Large backhoe at the Trapper Mine, Colorado, removing the coal and loading it into large trucks for delivery to a power plant just off the mining site. *(Edward A. Keller)*

Federal guidelines govern strip mining of coal in the United States. They require that mined land be restored to support its premining use. Restoration includes disposing of wastes, contouring the land, and replanting vegetation (**Figure 16.11**). The hope is that, after reclamation, the mined land will appear and function as it did before extraction of the coal. However, this is a difficult task and, in general, is not completely successful. The regulations also prohibit strip mining on prime agricultural land and

FIGURE 16.11 Reclaimed land at the Trapper Mine, Colorado The site in the foreground has just had the soil replaced after mining, whereas the vegetated sites have been entirely reclaimed. *(Edward A. Keller)*

give farmers and ranchers the opportunity to restrict or veto mining on their land, even if they do not own the mineral rights.

Underground mining of coal and other resources has also produced hazards and caused considerable environmental degradation. For example, (1) acid water draining from mines has polluted streams; (2) subsidence, collapse of the surface of the land into pits over underground mines, has damaged buildings, roads, and other structures; and (3) coal fires that start in mines can burn and smoke for years.

Future Use and Environmental Impacts of Coal. Limited resources of oil and natural gas and concerns about the energy supply in California and throughout the rest of the nation are increasing the demand for coal, and the coal industry is planning for increased mining activity. The crunch on the oil supply is still years away, but when it occurs, it will put pressure on the coal industry to open more and larger mines in both the eastern and the western coal beds of the United States. This solution to oil shortages could have significant environmental impacts for several reasons:[7,11,12]

- More and more land will be strip mined and will, thus, require careful restoration.
- Unlike oil and gas, burned coal leaves ash (5 percent to 20 percent of the original amount of the coal) that must be collected and disposed of in landfills. Some ash can be used as fill in land development or for other purposes, but about 85 percent is presently useless.
- Handling of tremendous quantities of coal through all stages—mining, processing, disposal of mining waste, shipping, burning, and disposing of ash—has potentially adverse environmental effects, including water pollution (see A Closer Look: Coal Sludge in the Appalachian Mountains); air pollution; release of trace elements likely to cause serious health problems into the water, soil, and air; and aesthetic degradation at mines, power plants, and other facilities associated with the coal industry.
- Fly ash, produced from burning finely ground coal in a power plant, collected in ash retention ponds adjacent to the power plant, is a potential hazard. The ash is toxic and must be disposed of. Ponds may hold several million cubic meters of wet ash. On December 22, 2008, the retaining structure of an ash pond at the Kingston Fossil power plant in Tennessee failed, sending a flood of ash and water downslope, destroying several homes, rupturing a gas line, and polluting a river.[13]
- Several billion metric tons of coal are burned worldwide, releasing huge amounts of carbon dioxide (CO_2) into the atmosphere. China, the United States, and Russia account for the majority of the carbon dioxide released. Carbon dioxide is a "greenhouse gas," thought to be significant in producing global warming. (Global warming is discussed in Chapter 18.)

Environmental problems associated with coal, although significant, are not necessarily insurmountable, and careful planning could minimize them. As world trade increases, new mines with cleaner coal will become more available. For example, coal mines being developed in Borneo are producing a low-grade but very low-sulfur coal that for coal is relatively clean. These clean coal deposits in Borneo are thick and have only a few meters of

A Closer Look

Coal Sludge in the Appalachian Mountains

Mining and processing coal in the Appalachian Mountains produces a lot of waste. Waste material, known as *coal sludge* or *slurry*, generated by processing coal, is a thick sludge composed of water, with particles of coal, rock, and clay. Coal sludge is often stored in impoundments behind a dam. West Virginia, Pennsylvania, and Kentucky have hundreds of coal sludge impoundments. There have been nine failures of coal sludge impoundments in the past 30 years. A coal-waste dam on Buffalo Creek, West Virginia, containing coal sludge failed in 1972. The resulting flood killed 118 people and destroyed about 500 homes. The Buffalo Creek event resulted in suggestions, recommendations, and regulations to minimize the chances of future events. Nevertheless, other events have occurred, including one on October 11, 2000, when about 1 million m^3 (250 million gal) of thick black coal sludge was released into the Big Sandy River system in southeastern Kentucky. The sludge was stored in an impoundment located over an abandoned coal mine. Collapse from the floor of the impoundment into the mine allowed the sludge to flow through the mine and into the environment over people's yards and roads and into a tributary to the Big Sandy River. Over 100 km (65 mi) of river was severely contaminated by the sludge. Life in the river, including several hundred thousand fish, was destroyed. The spill was one of the worst environmental disasters ever to occur in the southern United States. The same impoundment had a similar but smaller sludge spill in 1994 and was inspected as recently as 3 weeks before the October 2000 spill. Recommendations following the 1994 spill may not have been followed, and there was not sufficient hard rock above the abandoned mine to support the heavy sludge (**Figure 16.A**).[15]

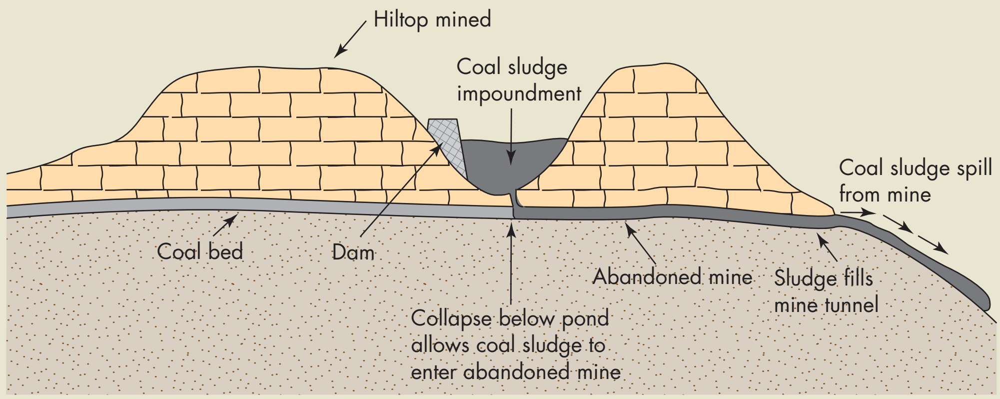


FIGURE 16.A Contamination by a coal sludge spill Idealized diagram of how a spill from a storage site with coal slurry might happen. In this case, collapse over an abandoned coal mine allows the slurry to spill.

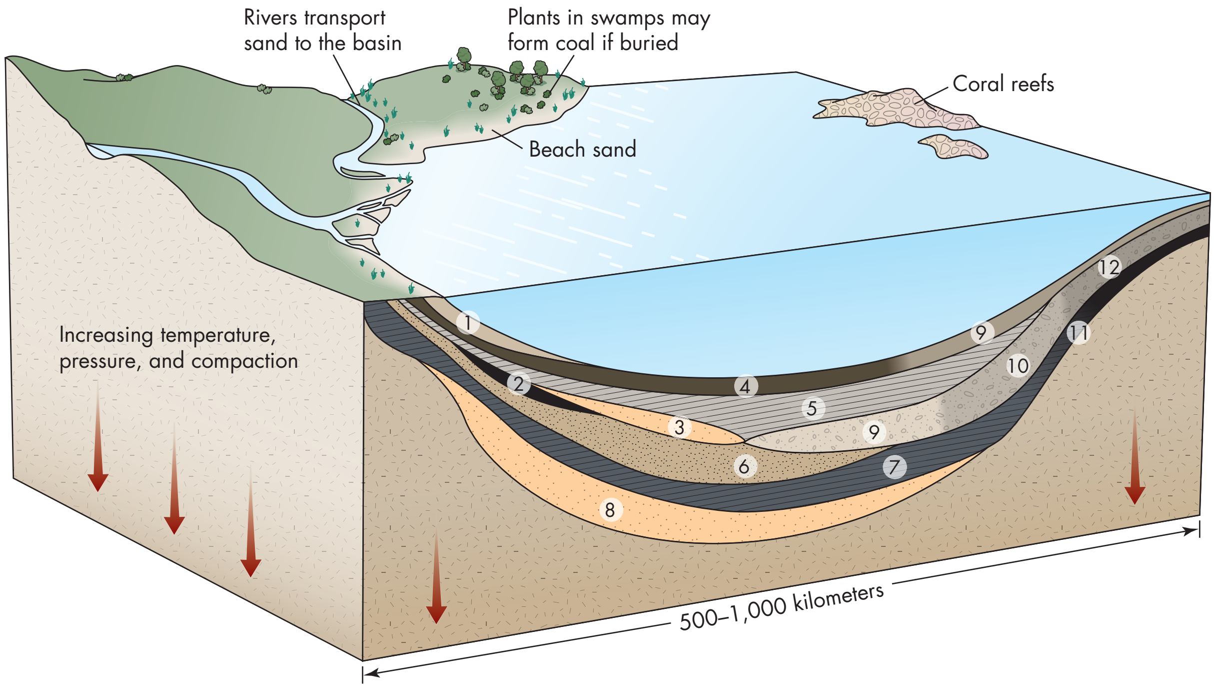
overburden.[14] Regardless of sources and quality, there may be few alternatives to mining tremendous quantities of coal. In the future, vast amounts of coal will be needed to feed thermoelectric power plants and to provide oil and gas by gasification and liquefaction of coal. An important objective is to find ways to use coal that minimize environmental disruption. Environmental costs in dollars of burning coal are becoming relatively high compared to those of using natural gas due to pollution abatement (i.e., cleaning coal and treating effluent from power plants). The cost of coal exceeds the cost of natural gas, so if discoveries and production of natural gas continue to grow as they did in 2010,

less coal (relative to natural gas) may be mined and burned in power plants.

Hydrocarbons: Oil and Gas

Oil, called crude oil, and natural gas are hydrocarbons, made up of carbon, hydrogen, and oxygen. **Natural gas** is mostly methane (CH_4). Methane usually makes up more than 80 percent of the energy gases present at a location. Other natural-energy gases include ethane, propane, butane, and hydrogen.[16] Like coal, the hydrocarbons are, for the most part, fossil fuels, in that they form from organic material that escaped complete decomposition after burial. Oil and gas are found in concentrated deposits, which have been heavily mined from wells. They are also found, in less readily available form, in oil shale and tar sands.

Geology of Oil and Gas Deposits. Next to water, oil is the most abundant fluid in Earth's crust, yet the processes that form it are only partly understood. Most Earth scientists accept that oil and natural gas are derived from organic materials that were buried with marine or lake sediments. Favorable environments where organic debris might escape oxidation include near-shore areas characterized by rapid deposition that quickly buries organic material, or deeper-water areas characterized by a deficiency in oxygen at the bottom that limits aerobic decomposition. In addition, the locations of oil and gas formation are generally classified as subsiding, depositional basins (**Figure 16.12**) in which older sediment is continuously buried by younger sediment; this sequence progressively subjects the older, more deeply buried material to higher temperatures and pressures.[17]



Explanation

1. Delta sand
2. Coal
3. Sandstone (compacted beach sand)*
4. Black mud settled from ocean water
5. Shale formed by compaction of mud
6. Brown sandstone (formed by compaction of river and delta sand)*
7. Ancient shale (the heat at this depth turns organic matter into oil)
8. Ancient sandstone*
9. Limestone*
10. Ancient reef*
11. Oil migrates from shale to the reef and forms an oil reservoir*
12. Dolomite formed by groundwater altering limestone*

**Potential future gas or oil reservoir*

FIGURE 16.12 Depositional basin Processes and deposits associated with formation of oil. *(Modified after Canadian Centre for Energy Information, 1999)*

Oil and natural gas originate primarily in fine-grained, organic-rich sediment, referred to as *source rock*. It is buried to depths of 1 to 3 km (0.6 to 2 mi) and subjected to heat and pressure that physically compress it. The elevated temperature and pressure, along with other processes, start the chemical transformation of organic debris into thermogenic oil and natural gas (**Figure 16.13**). Natural gas that

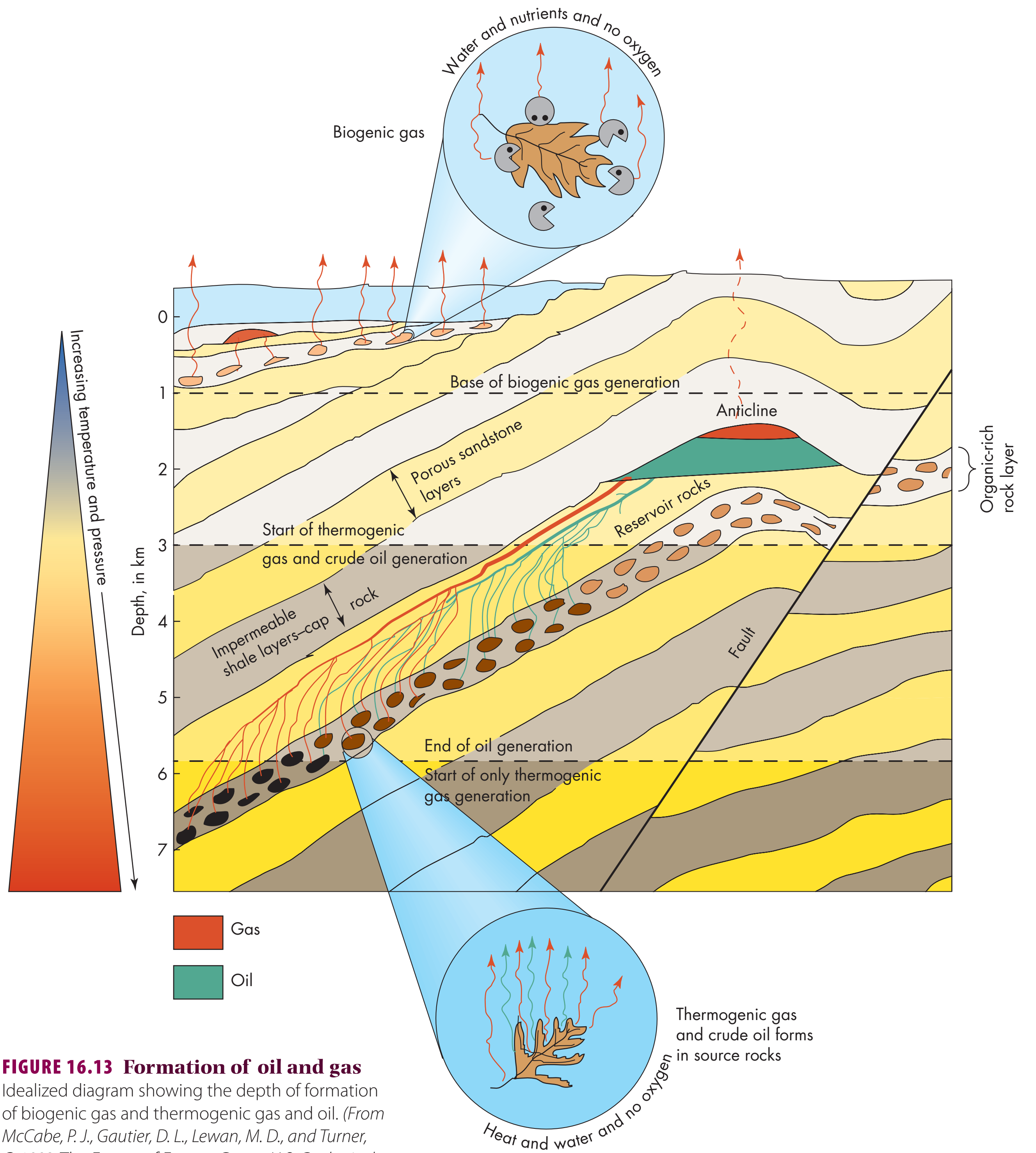


FIGURE 16.13 Formation of oil and gas
Idealized diagram showing the depth of formation of biogenic gas and thermogenic gas and oil. *(From McCabe, P. J., Gautier, D. L., Lewan, M. D., and Turner, C. 1993.* The Future of Energy Gases. *U.S. Geological Survey Circular 1115)*

forms close to the surface of Earth by biological processes is called *biogenic gas*. An example is the methane produced in landfills as waste decays. After their formation, the thermogenic hydrocarbons begin an upward migration to a lower-pressure environment with increased porosity. This primary migration through the source rock merges into secondary migration as the hydrocarbons move more freely into and through coarse-grained, more permeable rocks. These porous, permeable rocks, such as sandstone or fractured limestone, are called *reservoir rocks*. If the path is clear to the surface, the oil and gas migrate and escape there, and this may explain why most oil and gas are found in geologically young rocks (i.e., less than 100 million years old): Hydrocarbons in older rocks have had a longer time to reach the surface and leak out.[17] The entire process from initial deposition to deep burial often takes millions of years.[16] When oil and gas are impeded in their upward migration by a relatively impervious barrier, they accumulate in the reservoir rocks. If the barrier, or *cap rock*, has a favorable geometry, such as a dome or an anticline, the oil and gas will be trapped in their upward movement at the crest of the dome or anticline below the cap rock (Figure 16.13).[17] **Figure 16.14** shows an anticlinal trap and two other possible traps caused by faulting or by an unconformity, which is a buried erosion surface. These are not the only possible types of traps; any rock that has a relatively high porosity and permeability that is connected to a source rock containing hydrocarbons may become a reservoir. A reservoir will form if upward migration of the oil and gas is impeded by a cap rock that is positioned to entrap the hydrocarbons at a central high point.[14]

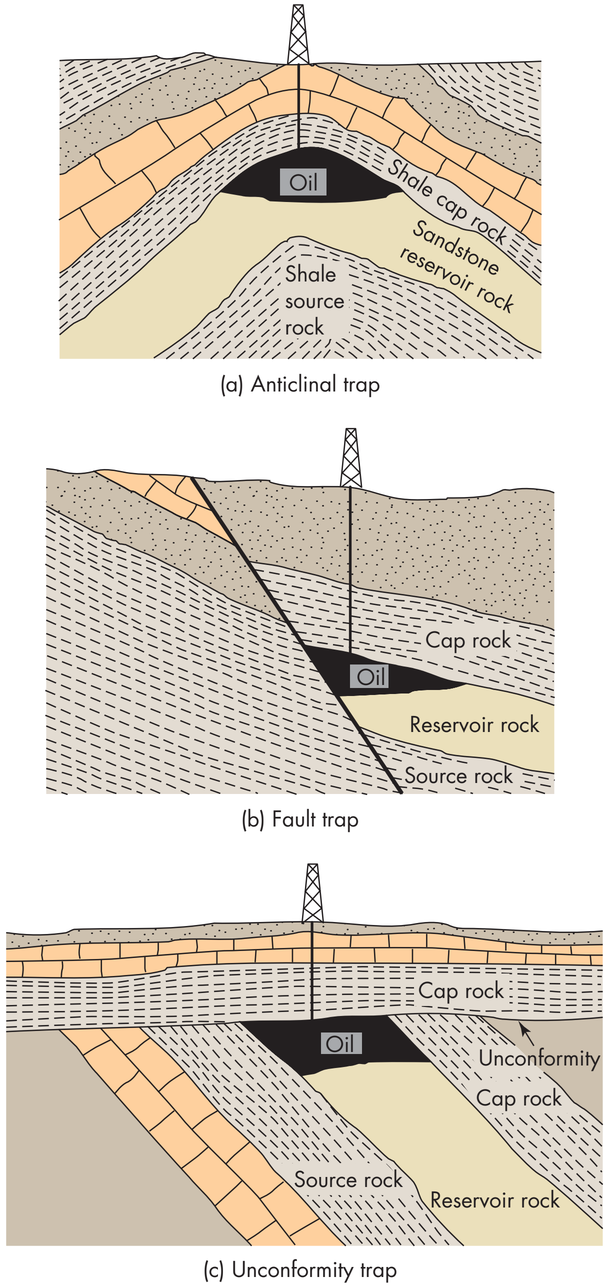


FIGURE 16.14 Types of oil traps (a) Anticlinal, (b) fault, and (c) unconformity traps.

Oil Production. Production wells in an oil field recover oil through primary or enhanced recovery methods. *Primary recovery* uses natural reservoir pressure to move the oil to the well, where it can then be pumped to the surface. Normally, this pumping delivers no more than 25 percent of the total petroleum in the reservoir. Increasing the recovery rate to 50 to 60 percent or more requires *enhanced recovery* methods. The enhancement manipulates reservoir pressure by injection of natural gas, water, steam, chemicals, or some combination of those, into the reservoir, pushing petroleum to wells where it can be lifted to the surface by means of the familiar "horse head" bobbing pumps, submersible pumps, or other lift methods.

Oil production always brings to the surface a variable amount of salty water, or brine, along with the oil. After the oil and water have been separated, the brine must be disposed of because it is toxic to the surface environment. Disposal can be accomplished either by injection as part of secondary recovery, evaporation in lined open pits, or deep-well disposal outside the field. Disposal sites in oil fields were some of the first hazardous-waste disposal facilities,

and some eventually became sites for the disposal of hazardous industrial wastes.

Distribution and Quantity of Oil and Gas. The distribution of oil and gas in space and geologic time is rather complex, but, in general, three principles apply:

1. Commercial oil is produced almost exclusively from sedimentary rocks deposited during the past 500 million years of Earth's history.
2. Although there are many oil fields in the world, most of the total production, plus reserves, occurs in a few percent of the producing fields.
3. Most of the world's giant oil fields are located near plate junctions that are known to have been active in the past 70 million years.

It is difficult to assess the petroleum reserves of the United States, much less those of the entire world. However, **Figure 16.15** shows a recent estimate of the world's reserves of crude oil. Most (62 percent) of the oil reserves are in the Middle East, and a high percentage of the natural gas reserves are in the former Soviet Union and the Middle East. However, recent large discoveries of natural gas in the United States suggest that reserves are growing, and that is good news. The numbers for crude oil do not suggest that we are going to run out of oil soon. However, there is uncertainty concerning the estimated size of the oil reserves and potential resources, and the peak in oil production, as mentioned earlier, will likely occur between 2020 and 2050.

Natural gas is a relatively clean fuel, compared with coal and oil, and it has the potential to replace coal and oil during the transition from fossil fuels to alternative energy sources. The worldwide amount of natural gas is very large, enough to last about a century at recent rates of consumption. Exploration for natural gas in the United States is ongoing, and considerable amounts of new gas are being found and developed. Two recent developments, coal-bed methane hydrates and tight natural gas from shale, will be discussed in this chapter as examples. These are considered nonconventional gas sources, but they are quickly becoming conventional in that they are widespread and growing. We will also briefly discuss methane hydrates, which may be a future source of natural gas.

Coal-Bed Methane. An "energy rush" is taking place in the coalfields of the western United States. The coal contains a large amount of methane stored on surfaces of the organic matter in the coal. Methane reserves in the Wyoming region, including the Wasatch and Power River basins, are sufficient to provide all the natural gas used by the United States for 5 years. More than 10,000 wells to recover the methane have already been drilled, and there may eventually be 10 times this many. **Coal-bed methane** (i.e., natural gas) wells are shallow and much more economical to drill than are typical oil wells. This relatively new source of methane is promising and will reduce the amount of energy we must import. However, there are environmental concerns associated with intensive development of coal-bed methane:[18]

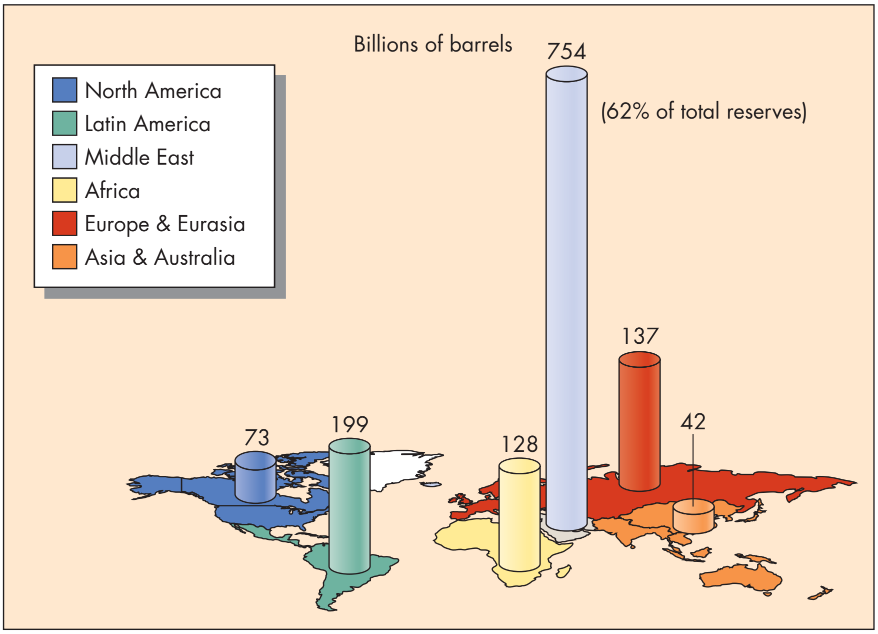


FIGURE 16.15 Oil reserves Proven world oil reserves (billions of barrels) in 2009. The Middle East dominates, with about two-thirds of total reserves. *(British Petroleum Company. 2010.* BP Statistical Review of World Energy 2009*)*

- Disposal of salty water that is produced with the methane
- Use of groundwater resources that could otherwise be used for agriculture
- Migration of methane (a flammable, explosive gas) away from well sites
- Reduction of crop production, if salty water is used to irrigate crops
- Pollution of stream water and loss of spring flow as groundwater is extracted and disposed mine water enters streams and rivers
- Erosion and runoff of land disturbed for roads, well sites, processing, and transportation of methane

In summary, coal-bed methane is an important energy source. However, its extraction, processing, and transportation to users must be closely evaluated to determine how best to reduce or eliminate potential adverse environmental effects. Then, steps to protect the environment should be implemented in the form of laws and policy, just as we attempt to do for other types of energy exploitation and use. Extraction of any fossil fuel is inherently a process with potential to harm the environment, and coal-bed methane is not an exception.

Black Shale (Tight Natural Gas). Devonian shale buried 1 km or so beneath northern Appalachia contains as much as 500 trillion ft^3 of natural gas, of which 10 percent is a potential resource. The methane, known as **tight gas**, is distributed in very small tight openings throughout the black shale. Tight gas is an unconventional reservoir compared to conventional natural gas reservoirs where methane is in pockets related to geologic structure (see figure 16.13). The vast area dominated by the Marcellus Shale (that contains tight gas) is shown in Figure 16.16.[19] Recovery of the methane is costly, as deep wells that turn at depth to a horizontal position are necessary (Figure 16.17). Water and other chemicals are then used to fracture the rocks (i.e., hydrofracturing) to facilitate recovery of the gas. Most of the gas is in very small pore spaces in the fine-grained shale, with some gas also in vertical fractures (i.e., joints) and some adsorbed on mineral grains and organic material in the rock.

An energy rush is now occurring to recover tight natural gas. Thousands of new wells have been permitted in Pennsylvania alone (see photograph opening this chapter). Other areas with tight gas include the Barnett Shale in Texas, the Haynesville Shale in Louisiana, and the Fayetteville Shale in Arkansas. Property owners in promising areas of Pennsylvania are receiving signing bonuses of up to $2,000 per acre, and gas royalties from a single large well can be financially rewarding. Many thousands of new jobs could come to the region as the gas fields are developed.

There is concern that drilling and hydrofracturing could result in contamination of water resources. The wells require a lot of water, and chemicals are also used as part of the extraction process. About 34,000 m^3 (9 million gal) of wastewater per day was produced in 2009 by gas wells in Pennsylvania alone. Also, the natural water in the shale where gas is extracted may have contaminants, such as the metal cadmium and benzene (a toxic hydrocarbon), as well as methane. The wastewater also contains dissolved salts that can render the water several

FIGURE 16.16 Tight gas Devonian shales in the northeastern United States hold abundant natural gas that is fueling an energy rush. *(U.S. Geological Survey)*

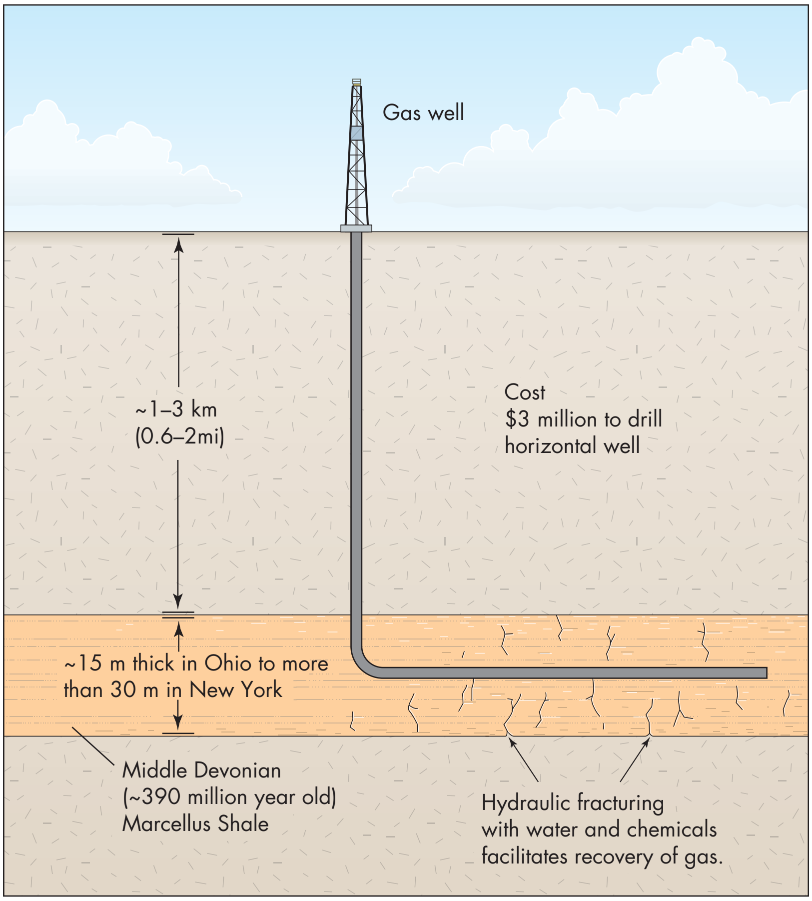


FIGURE 16.17 Gas well in tight shale The deep well turns at depth to horizontal.

times as salty as seawater. As a result, wastewater from gas wells can be a serious water pollutant. Reportedly, the Monongahela River in Pennsylvania has been contaminated by salty water, presumably from wastewater from gas wells. The salty water corroded equipment in power plants that extracted water from the river, and residents reported that dishwashers were malfunctioning. The quick fix was to reduce the amount of wastewater from the drilling that was discharged to the river and release water from upstream dams to dilute the pollutants. A long-term solution will require water treatment plants for the wastewater. However, the rate of production of wastewater from gas drilling in Pennsylvania may double in coming years, requiring several new treatment plants; a typical plant can handle about 1,500 m^3 (0.4 million gallons) of wastewater per day. Several present sewage wastewater treatment plants on the Monongahela River have treated some wastewater from gas drilling, but treatment plants (each costing as much as several tens of millions of dollars) dedicated to the wastewater from the gas drilling may be necessary.

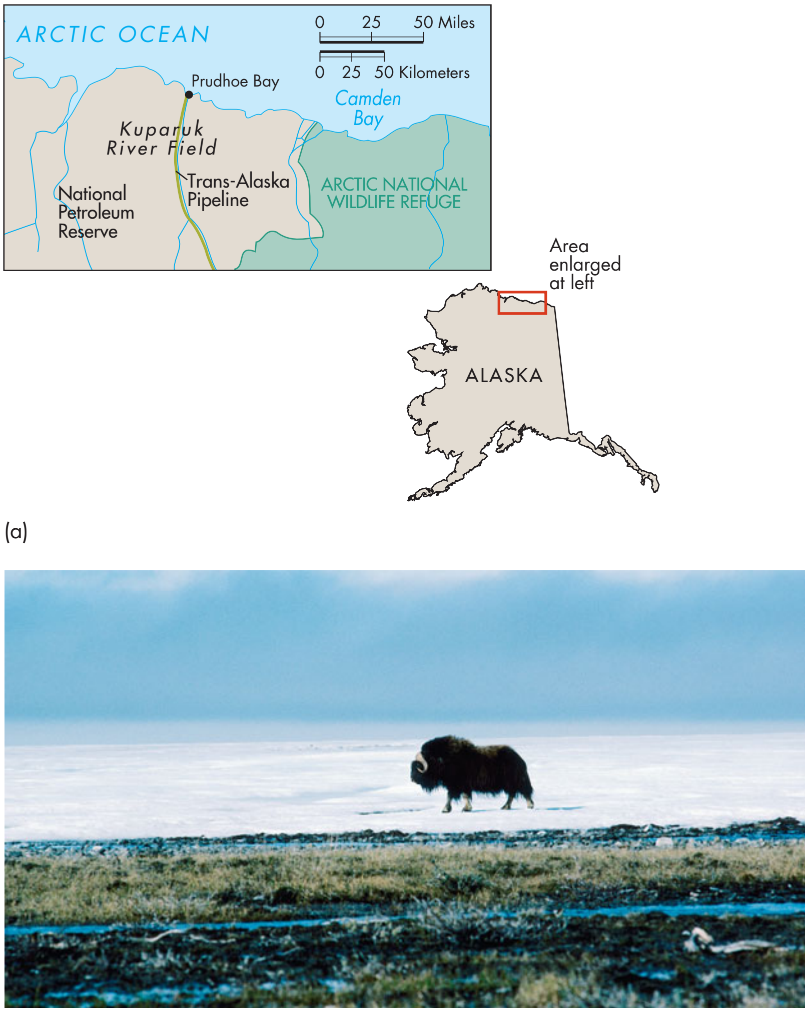
A gas well being drilled in Pennsylvania in June 2010 had a blowout failure that released gas and wastewater at the surface. Fortunately, an explosion did not occur, and pollution by wastewater did not continue for a long time. However, such blowouts could be catastrophic, as we learned from the oil spill in the Gulf of Mexico in 2010. The U.S. Environmental Protection Agency has been directed to study safety issues associated with drilling for natural gas, and a report is due out in 2012. The city of New York is very concerned that drilling could contaminate its water supply, which comes from upstate New York. The city has all but banned drilling gas wells in watersheds from which the city receives its water supply.

Methane Hydrate. It has been known for years that methane hydrate deposits exist at depths of about 1,000 m (3,300 ft) beneath the sea. *Methane hydrate* is a white, ice-like material composed of molecules of methane gas surrounded by "cages" of frozen water. The frozen water cages are formed as a result of microbial digestion of organic matter in the sediments. Methane hydrate deposits are also found on land; the first land deposits discovered were in permafrost areas of Siberia and North America, where they are called *marsh gas*.

Methane hydrate deposits are found throughout both the Pacific and Atlantic Oceans. Methane hydrates in the marine environment are a potential resource, with approximately twice as much carbon as all the other known natural gas, oil, and coal deposits on Earth.[20] Methane hydrate deposits have the potential to supply some of the energy needs of the world in the future, if they can be captured. Furthermore, present gas deposits on land are plentiful, and extraction is not expensive.

Impact of Exploration and Development. The environmental impact of oil and gas exploration and development varies from negligible—such as remote-sensing techniques used in exploration—to significant—such as the unavoidable impact of projects like the Trans-Alaska Pipeline. The impact of exploration for oil and gas can include building roads, conducting exploratory drilling, and building a supply line to remote areas. Except in sensitive areas, including some semiarid-to-arid environments and some permafrost areas, these activities generally cause few adverse effects to the landscape and resources.

Development of oil and gas fields involves drilling wells on land or beneath the sea; disposing of wastewater brought to the surface with the petroleum; transporting the oil by tankers, pipelines, or other methods to refineries; and converting the crude oil into useful products. At every step, there is a well-documented potential for environmental disruption, including problems associated with wastewater disposal, accidental oil spills, leaking pipes in oil fields, shipwrecks of tankers, and air pollution at refineries. For instance, serious oil spills along the coastlines of Europe and North America have spoiled beaches, estuaries, and harbors; killed marine life and birds; polluted groundwater and surface water; and caused economic problems for coastal areas that depend on tourist trade.



(a)

(b)

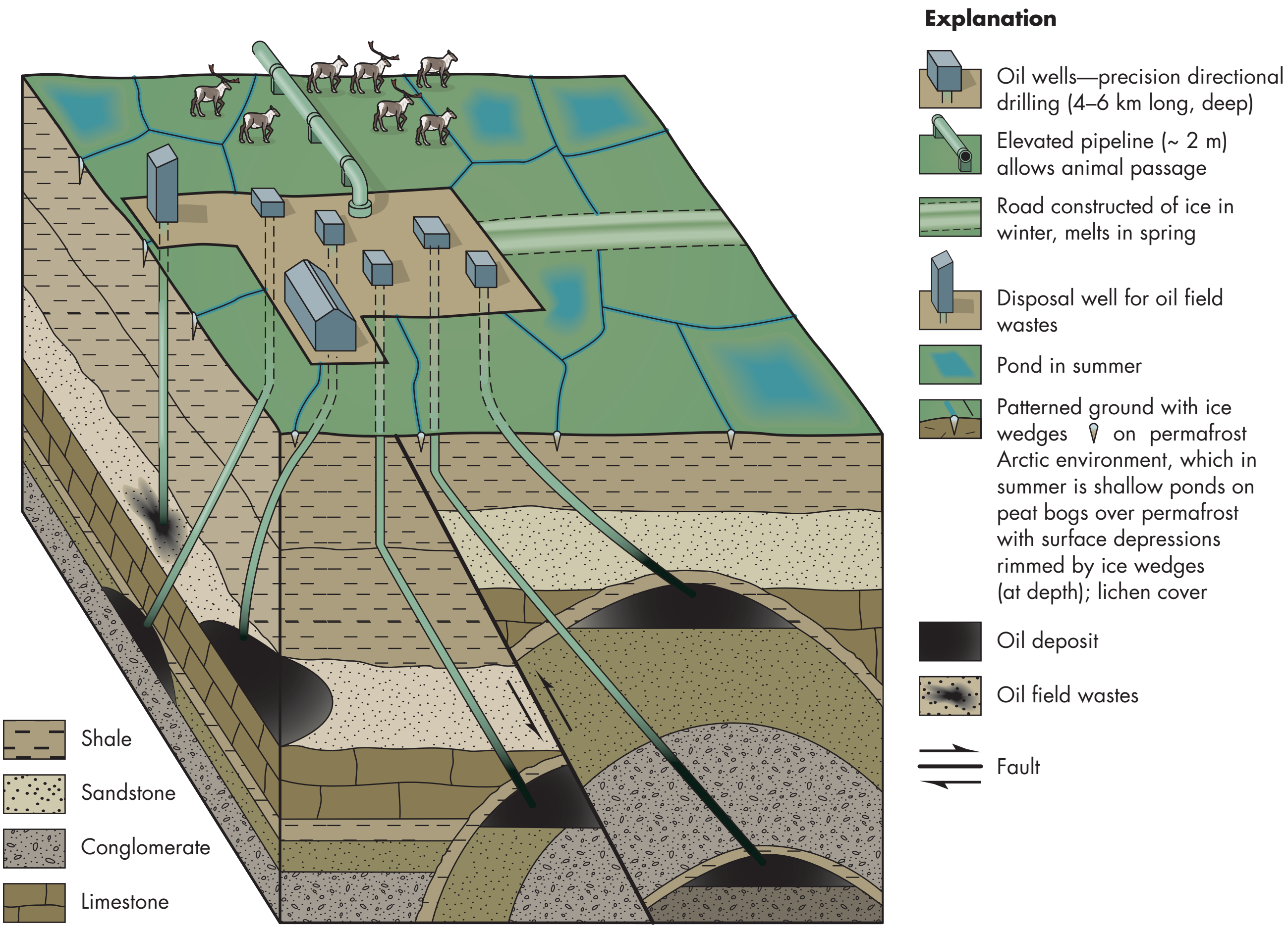
FIGURE 16.18 Arctic National Wildlife Refuge (a) Map, with location of the Arctic National Wildlife Refuge. (b) Mountains, plains, and wildlife of the area. *(Ted Kerasote/Photo Researchers, Inc.)*

As a result of current energy shortages, there is pressure to develop new oil fields in offshore areas and wilderness areas, such as the Arctic National Wildlife Refuge (ANWR) in Alaska, where several billion barrels of oil are located (**Figure 16.18**).

The argument in favor of exploration and development of oil in ANWR is threefold. First, the United States needs more oil, and the oil in ANWR would reduce the amount of oil we import. Second, new oil development will bring jobs and economic growth to Alaska. Third, new techniques for exploration and drilling of oil wells have caused less adverse environmental damage than previous development (**Figure 16.19a**).

These techniques include:

- Using directional drilling from central locations where many wells form a single site, spread out underground like the spokes of a bicycle wheel (Figure 16.19a). This technique reduces the land area disturbed by drilling to sites of about 40 ha (100 acres).
- Elevating pipelines above ground to allow animal migration (Figure 16.19b).
- Avoiding construction of permanent roads. Roads are made of ice in the winter and melt in the summer (Figure 16.19a).



(a)

(b)

FIGURE 16.19 New oil drilling and transport technology (a) Some of the new technology that could reduce the impact of developing oil at the Arctic National Wildlife Refuge. (b) Caribou crossing beneath an elevated pipeline. *(U.S. Fish and Wildlife Service/Getty Images)*

Opponents of the exploration and development of oil in ANWR contend that:

- Even the most favorable technology will adversely affect ANWR.
- Some wilderness areas should remain wilderness, and drilling will permanently change ANWR.
- Development of oil fields is inherently damaging because it requires an extensive industrial complex of machines, vehicles, pipelines, and people.
- The oil beneath ANWR will not be a significant contribution to the U.S. oil supply. Although it would be spread out over decades, providing a few percent of our total oil consumption during that time, in total, the ANWR oil itself would provide only about a 6-month to 2-year supply of oil.

The decision concerning development of oil at ANWR reflects the relationship between science and values. Science says we can develop the oil with less environmental damage than in the past. But even "less than in the past" may be too much. Our values will be determined by balancing our economic need for oil against our desire to preserve a pristine wilderness area.

Impact of Use. A familiar and serious impact associated with oil is air pollution produced in urban areas when fossil fuels are burned to produce energy for electricity, heat, and automobiles. Also, as does burning coal, burning oil and gas releases carbon dioxide, the major human-produced greenhouse gas (see Chapter 18).

Oil Shales and Tar Sands. Recovering petroleum from surface or near-surface oil shale and tar sands involves the use of well-established techniques. We need economic methods for developing oil shale resources that will minimize environmental disruption.

Oil shale is a fine-grained sedimentary rock containing organic matter that, when heated, yields significant amounts of oil and gas—oil yield is generally 100 to 200 L per ton of oil shale—that are otherwise insoluble in ordinary petroleum solvents. This process is known as *destructive distillation*. The best-known oil shales in the United States are found in the 50-million-year-old Green River Formation that underlies parts of Colorado, Utah, and Wyoming. The Green River Formation consists of oil shale interbedded with variable amounts of sandstone, siltstone, claystone, and compacted volcanic ash. The oil shale resource is huge. About 100 billion barrels of oil could potentially be recovered. Mining of oil shale, using known technology, is expensive. Nevertheless, as oil prices rise, oil-shale mining is being reconsidered.[21]

Tar sands are rocks that are impregnated with tar oil, asphalt, or other petroleum materials. The recovery of any of these petroleum materials by traditional methods is not commercially possible. The term *tar sand* is somewhat confusing because it includes several rock types, such as shale and limestone, as well as unconsolidated and consolidated sandstone. However, these rocks all contain a variety of semiliquid, semisolid, and solid petroleum products. Some of these products ooze from the rock; others are difficult to remove, even with boiling water.[22] Although similar to oil pumped from wells, the oil from tar sands is much more viscous and, therefore, more difficult to recover. One possible conclusion concerning the geology of tar sands is that they form in essentially the same way as the more fluid oil but, because much more of the volatiles and accompanying liquids in the reservoir rocks have escaped, the more viscous components remain as tar sands.

Large accumulations of tar sands have been identified. For example, the Athabasca Tar Sands of Alberta, Canada, cover an area of approximately 78,000 km^2 (30,116 mi^2) and contain an estimated reserve of 300 billion barrels of oil that might be recovered. About half of it (173 billion barrels) can be economically recovered today. These tar sands are now yielding about 1 million barrels of synthetic crude oil per day from large strip mines.[22] Today, the United States imports more oil from Canada than from any other country (19 percent), and, of this, about one-half comes from oil sands.[14,22]

16.5 Future of Oil

Recent estimates of proven oil reserves in the world suggest that, at present production rates, oil and natural gas will last a few decades.[5,23] However, the important question to ask is not how long oil will last at present and future production rates, but at

what point will we reach peak production? This question is important because, once we have reached peak production, less oil will be available, and there will be shortages and price shocks. The world oil production peak is likely to occur within the lifetime of many people living today,[24] much sooner than generally expected by most people. As a result, there may be little time left to adjust to potential changes in lifestyle and economies in a postpetroleum era. Walter Youngquist, an energy expert, argues that we are fortunate to be living in a prosperous period of human history, made possible by our inheritance of a 500-million-year period of oil-forming processes.[24] We will never entirely run out of crude oil, but people of the world currently depend upon oil for about 40 percent of their energy, and significant shortages will cause major problems.[24,25]

The following factors provide evidence that we are heading toward a potential crude oil crisis:

- We are approaching the time when approximately one-half of the total crude oil from traditional oil fields on Earth will have been consumed.[24] Revisit peak oil (section 16.2) near the beginning of this chapter. Recent estimates suggest that the world may have about 20 percent more oil awaiting discovery than predicted a few years ago. Furthermore, more oil exists in known fields than was earlier thought. However, the United States has already consumed approximately half of its oil resources, necessitating additional oil imports in the future.
- Proven world reserves total approximately 1 to 2 trillion barrels.[3,25] It is estimated that about 3 trillion barrels of crude oil may ultimately be recovered from remaining oil resources.
- World consumption today is about 31 billion barrels per year (85 million barrels per day), and, for every 3 barrels of oil consumed, only 1 barrel is discovered.[25]
- The predicted decline in oil production is based on the estimated amount of oil that may ultimately be recoverable, as well as on projections of new discoveries and rates of future consumption. The peak in world crude oil production (35 billion barrels per year) is predicted to occur from about 2015 to 2030, depending upon whether you are an optimist or a pessimist.[23] Production of 35 billion barrels per year is nearly a 10 percent increase over production today. Whether or not you believe the increased production will be a problem depends on your view of predicted shortages, based on the past history of oil consumption. We have survived several predicted shortages in the past. However, most oil experts believe that peak oil is only a few decades away.[5,6]
- It is predicted that significant production of oil in the United States will not extend beyond the year 2090. The world production of oil will be nearly exhausted by 2100.[25]

What is an appropriate response to these statements? We need to begin with a major educational program that informs both people and governments of the potential oil depletion in the twenty-first century. We are currently operating in ignorance or denial in the face of a potentially serious situation. Planning and education are important in order to avoid future military confrontations like the Gulf War and food shortages due to the reduced availability of oil to produce fertilizers for agriculture. Before significant oil shortages occur, we should transition from oil to: natural gas with gasification and liquefaction of our tremendous coal reserves; oil and gas from oil shale; atomic energy; and alternative energy sources, including solar energy, wind power, and hydrogen. Following the transition, the vast majority of our energy should come from sources that are environmentally clean, safe, and sustainable. Changes during the transition from oil will strongly effect our present petroleum-based society. However, there appears to be no insurmountable problem if we implement meaningful short- and long-range plans to simultaneously phase out oil, transition to natural gas, and phase in alternative energy sources.

Having obtained a better understanding of the nature and abundance of the fossil fuels, we will now turn to the topic of acid rain, a major environmental consequence of burning fossil fuels.

16.6 Fossil Fuel and Acid Rain

Acid rain is thought to be a regional to global environmental problem related to the burning of fossil fuels. Although acid rain is caused primarily by coal

burning, gasoline combustion also contributes to the problem. *Acid rain* refers to both wet and dry acid deposition. *Wet* acid deposition occurs when pollutants, acid precursors such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), react with water vapor in the atmosphere, producing acids. *Dry* acid deposition occurs when the particles containing acid precursors fall to Earth and then react with water to produce acids. Therefore, although the term *acid rain* is more commonly used, *acid deposition* is a more precise term. **Acid rain** is defined as precipitation whose pH is below 5.6. The pH is a numerical value of the relative concentration of hydrogen ions (H^+) in a solution that is used to describe the solution's acidity. A solution with a pH of 7 is a neutral solution, one that is neither acidic nor basic. Natural rainfall is slightly acidic with a pH of approximately 5.6, caused by water in the atmosphere combining with carbon dioxide to produce a weak carbonic acid ($H_2O + CO_2 \rightarrow H_2CO_3$). The pH scale is a negative logarithmic scale; for example, a pH value of 3 is 10 times more acidic than a pH value of 4 and 100 times more acidic than a pH value of 5 (**Figure 16.20**). Rainfall in Wheeling, West Virginia, was once measured at a pH value of 1.5, nearly as acidic as stomach acid, and pH values as low as 3 have been recorded in other locations.

Today, burning of fossil fuel in the United States annually releases about 17 million tons of nitrogen oxide and 13 million tons of sulfur dioxide into the atmosphere. After emission, these oxides are transformed to sulfate (SO_4) or nitrate (NO_3) particles that can combine with water vapor to eventually form sulfuric (H_2SO_4) and nitric (HNO_3) acids. These acids may travel long distances with prevailing winds and be deposited as acid rain (**Figure 16.21**). The acid rain problem we are most familiar with results from sulfur dioxide, which is primarily emitted from burning coal in power plants that produce electricity in the eastern United States.

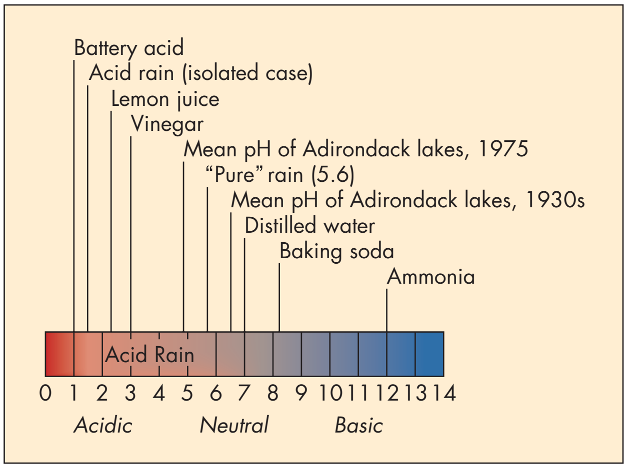


FIGURE 16.20 The pH scale Values for a variety of materials are shown. *(Modified after U.S. Environmental Protection Agency, 1980)*

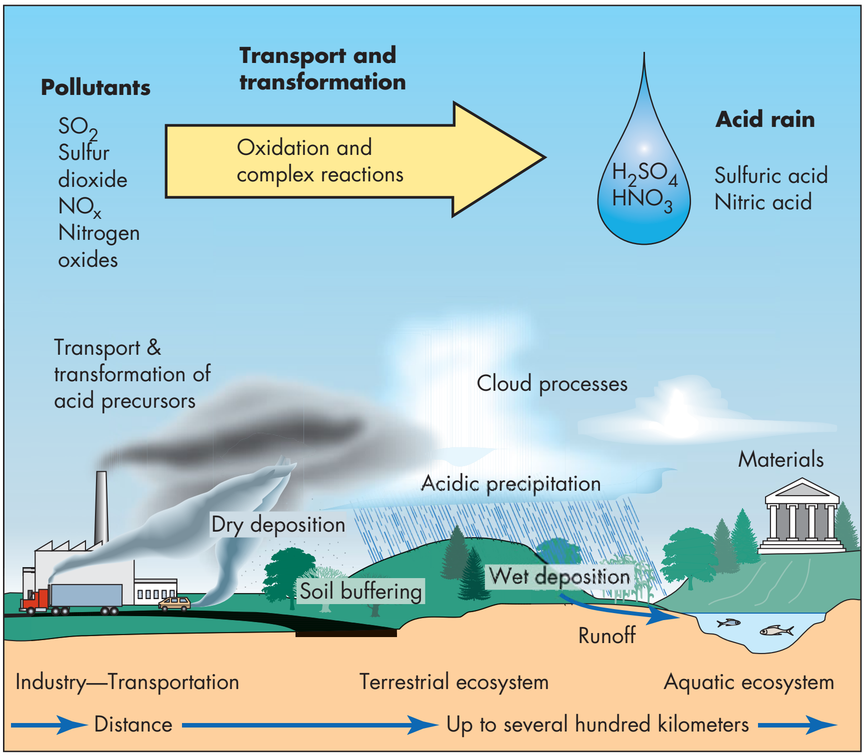


FIGURE 16.21 How acid rain forms Paths and processes associated with acid rain. *(Modified after Albritton, D. L., as presented in Miller, J. M.)*

Environmental Effects of Acid Rain

Geology, climate patterns, type of vegetation, and composition of soil all affect potential impacts of acid rain. **Figure 16.22** shows areas in the United States that are sensitive to acid rain, and identification of

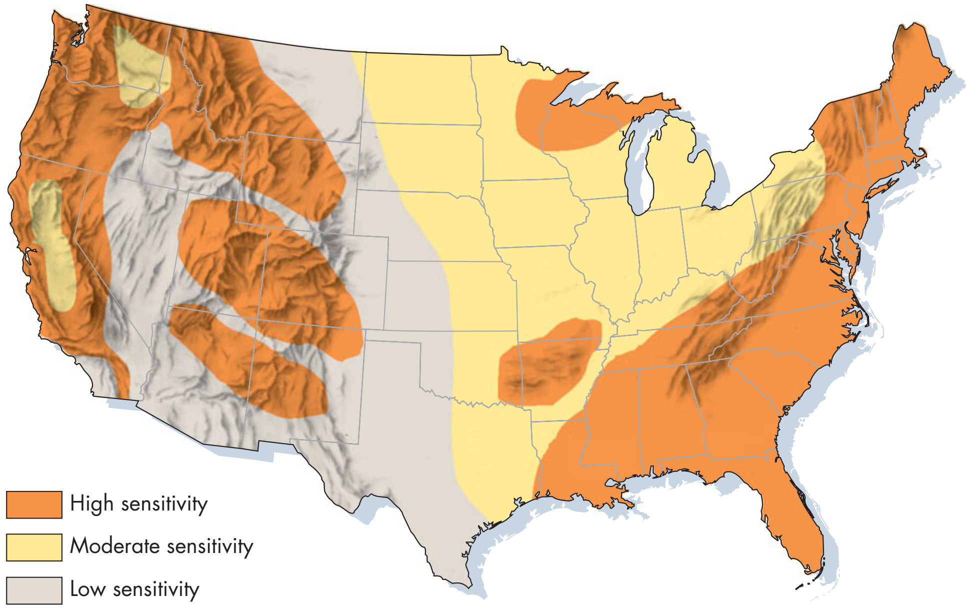


FIGURE 16.22 Areas in the United States that are sensitive to acid rain *(From U.S. Environmental Protection Agency, 1980)*

these areas is based on some of the above-mentioned factors. Particularly sensitive areas are those in which the bedrock, soils, or water cannot buffer the acid input. For instance, areas dominated by granitic rocks have little buffering action. *Buffering* refers to the ability of a material to neutralize acids. These materials, known as *buffers*, include calcium carbonate or calcite ($CaCO_3$), found in many types of soils and rock, such as limestone. The calcium carbonate reacts with and removes the hydrogen ions in the acidic water by forming bicarbonate ions (HCO_3^-) and neutralizing the acid.

The major environmental effects of acid rain include:

- **Damage to vegetation.** Acid rain is detrimental to vegetation, especially forest resources, such as evergreen trees in Germany and red spruce trees in Vermont. The soil's fertility may be reduced, either because nutrients are leached out by the acid or because the acid releases toxic substances into the soil. This is the main effect of acid rain on vegetation.
- **Damage to lake ecosystems.** Acid rain may damage lake ecosystems by (1) disrupting the life cycles of fish, frogs, and crayfish and (2) interfering with the natural cycling of nutrients and other chemical elements necessary for life. The acid rain tends to keep the nutrients in solution, so that they leave the lake rather than being cycled in the system. As a result, aquatic plants may not grow, and animals that feed on these plants have little to eat. This degradation is passed up the food chain to the fish and other larger animals. Examples of adverse effects of acid rain on lake systems have been found in Canada and Scandinavia.
- **Damage to human structures.** Acid rain damages building materials, plastics, cement, masonry, galvanized steel, and several types of rocks, especially limestone, sandstone, and marble (**Figure 16.23**). In cities around the world, irreplaceable statues and buildings have been significantly damaged, resulting in losses of billions of dollars per year.

A Solution to the Acid Rain Problem

Lake acidification can be offset by periodic addition of a buffer material, such as calcium carbonate. Although this remedy has been used in several areas, including New York State, Sweden, and Canada, adding buffer material to lakes is a short-term, expensive solution to lake acidification. The only practical long-term solution to the acid rain problem is to reduce the emissions of the chemicals that cause the problem. From an environmental viewpoint, the best way to reduce emissions is to practice strong energy conservation, which would result in lower emissions. The second-best way is to treat the coal before, during, and after burning, in order to intercept the sulfur dioxide before it is released into the

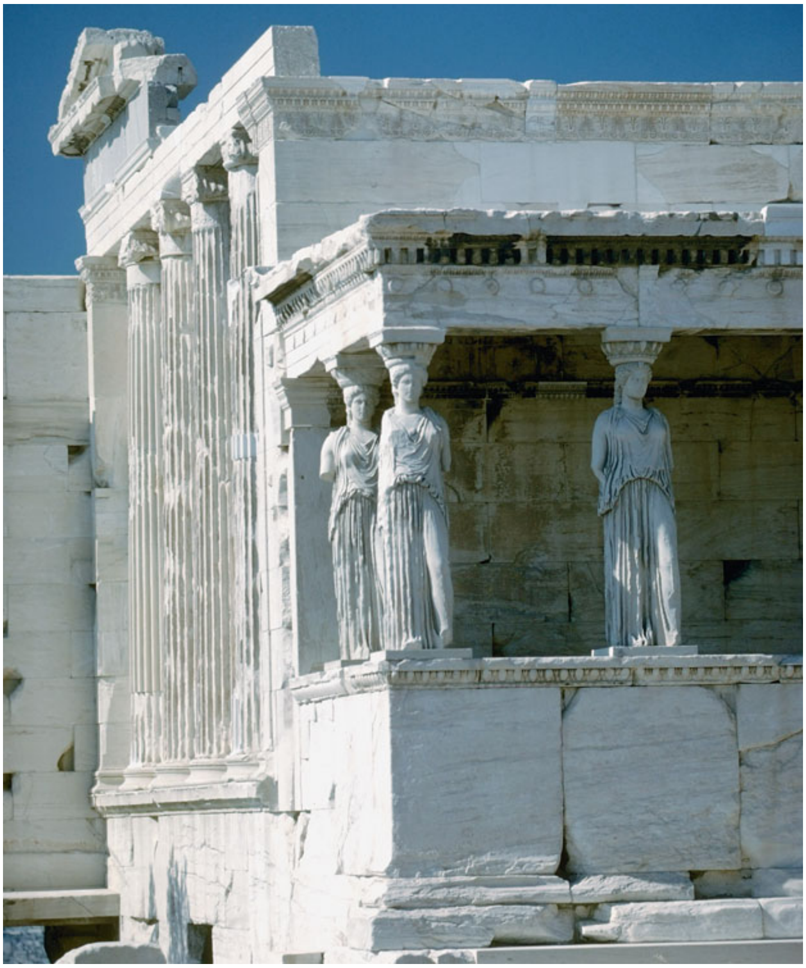


FIGURE 16.23 Acid rain damages stone Air pollution and acid rain are damaging buildings and statues in many urban regions. Shown here is the Acropolis in Athens, Greece. Statues here have been damaged to such an extent that originals have been placed inside buildings in specially constructed glass containers. *(Peter Christopher/Masterfile)*

environment. Reduction of nitrogen oxide is more difficult because it is primarily caused by gasoline burning in automobiles. Nevertheless, control strategies exist to reduce emissions of SO_2 and NO_x. It is encouraging that the reduction of pollutants causing acid rain is a successful national and international goal. Unfortunately, the acid rain problem will not go away soon, even with lower emissions of acid precursors. Acid deposition has been accumulating in soils for decades, and its effects will linger for decades to come.[26,27]

16.7 Nuclear Energy

Energy from Fission

Production of **nuclear energy** relies mostly on fission. *Nuclear fission* is the splitting of atomic nuclei by neutron bombardment. Fission of the nucleus of a uranium-235 atom, for example, releases three neutrons, fission fragments composed of the nuclei of radioactive elements that are lighter than uranium, and energy in the form of heat (see A Closer Look: Radioactivity). The released neutrons strike other U-235 atoms, releasing more neutrons, fission products, and heat. The process continues in a *chain reaction*, and, as more and more uranium is split, it releases ever more neutrons (**Figure 16.24**, page 564). An uncontrolled chain reaction—the kind used in nuclear weapons—leads quickly to an explosion. However, sustained or stable nuclear reactions in reactors are used to provide heat for the generation of electricity.

The first controlled nuclear fission was demonstrated in 1942, leading the way for the use of uranium in explosives and as a heat source that provides steam for electricity generation. Fission of 1 kg (2.2 lb) of uranium releases approximately the same amount of energy as the burning of 16 metric tons of coal.

A Closer Look

Radioactivity

All atoms of the same element have the same atomic number; that is, they have the same number of protons in the nucleus. Isotopes are atoms of an element that have different numbers of neutrons and, therefore, different atomic masses, defined by the number of protons plus the number of neutrons in the nucleus. For example, two isotopes of uranium are $^{235}U_{92}$ and $^{238}U_{92}$. The atoms of both of these isotopes have an

Radiation emitted			Radioactive elements	Half–life		
Alpha	Beta	Gamma		Minutes	Days	Years
☢		☢	Uranium–238 ↓			4.5 billion
	☢	☢	Thorium–234 ↓		24.1	
	☢	☢	Protactinium–234 ↓	1.2		
☢		☢	Uranium–234 ↓			247,000
☢		☢	Thorium–230 ↓			80,000
☢		☢	Radium–226 ↓			1,622
☢			Radon–222 ↓		3.8	
☢	☢		Polonium–218 ↓	3.0		
	☢	☢	Lead–214 ↓	26.8		
	☢	☢	Bismuth–214 ↓	19.7		
☢			Polonium–214 ↓	0.00016 (sec.)		
	☢	☢	Lead–210 ↓			22
	☢		Bismuth–210 ↓		5.0	
☢		☢	Polonium–210 ↓		138.3	
None			Lead–206	Stable		

FIGURE 16.B Decay chain and half-lives from radioactive U-238 to stable lead-206.
(From Schroyer, F., ed. 1985. Radioactive Waste, 2nd ed. American Institute of Professional Geologists)

atomic number of 92, but their atomic mass numbers are 235 and 238, respectively. These isotopes may be written as uranium-235 and uranium-238, or U-235 and U-238, respectively.

Some isotopes, called *radioisotopes*, are radioactive and spontaneously undergo nuclear decay. Nuclear decay occurs when a radioisotope undergoes a nuclear change while emitting one or more forms of radioactive radiation. The three major kinds of radiation emitted during nuclear decay are called alpha particles (α), beta particles (β), and gamma radiation (γ). Each radioisotope has its own characteristic emissions; some isotopes emit only one type of radiation, while others emit a mixture of radiation types.

Alpha particles consist of two protons and two neutrons, making them much more massive than other types of radioactive emission. Because alpha decay, emission of an alpha particle, changes the number of protons and neutrons in the atom's nucleus, the isotope is changed into an isotope of a different element. For example, a radon-222 atom, which has 86 protons, emits an alpha particle and is thereby transformed into a polonium-218 atom, which has 84 protons. Because of their great mass, alpha particles are the slowest-moving of the radioactive emissions and have the lowest energy. They travel the shortest distances—approximately 5 to 8 cm (2 to 3 in.) in air—and penetrate solid matter less deeply than do beta or gamma emissions.[29]

Beta particles are energetic electrons that have a small mass compared with alpha particles. Beta decay occurs when one of the neutrons in the nucleus of the isotope spontaneously changes.[29] Note that the electron emitted is a product of the transformation; remember that electrons are found surrounding the nucleus, not in it.

In gamma radiation, gamma rays are emitted from the isotope, but the number of protons and the number of neutrons in the nucleus are unchanged. Gamma rays are similar to medical X-rays, but they are usually more energetic and more penetrating. Gamma rays have the highest energy of all radioactive emissions; they travel faster and farther and penetrate more deeply than do alpha or beta particles.

An important characteristic of a radioisotope is its half-life, which is the time required for one-half of a given amount of the isotope to decay to another form. Every radioisotope has a unique, characteristic half-life. Radon-222, for example, has a relatively short half-life of 3.8 days. Carbon-14, a radioactive isotope of carbon, has a half-life of 5,570 years; U-235 has a half-life of 700 million years; and U-238 has a half-life of 4.5 billion years.

Some radioisotopes, particularly those of very heavy elements, undergo a series of radioactive decay steps, until they finally become a stable, or nonradioactive, isotope. **Figure 16.B** shows the decay chain from U-238 through radium-226, radon-222, and polonium-218 to the stable isotope of lead-206. The two most important facts about each transformation are the type of radiation emitted and the half-life of the isotope that is transformed (Figure 16.B). The decay from one radioisotope to another is often stated in terms of parent and daughter atoms. For example, the parent radon-222, a gas with a half-life of 3.8 days, decays by alpha emission to its daughter, polonium-218, a solid with a half-life of 187 seconds.[29]

Three isotopes of uranium are found in a naturally occurring uranium sample: U-238, which accounts for approximately 99.3 percent of natural uranium; U-235, which makes up just under 0.7 percent; and U-234, which makes up about 0.005 percent. Uranium-235 is the only naturally occurring fissionable material and is, therefore, essential to the production of nuclear energy. Naturally occurring uranium is processed to increase the amount of U-235 from 0.7 percent to about 3 percent before it is used in a reactor. The processed fuel is called *enriched uranium*. Uranium-238 is not naturally fissionable, but it is "fertile material" because, upon bombardment by neutrons, it is converted to plutonium-239, which is fissionable.[28]

Geology and Distribution of Uranium

The natural concentration of uranium in Earth's crust averages approximately 2 parts per million (ppm). Uranium originates in magma and is concentrated to about 4 ppm in granitic rock, where it is found in a variety of minerals. Some uranium is also found in late-stage igneous rocks, such as pegmatites.

Uranium forms a large number of minerals, many of which have been found and mined. Three types of deposits have produced most of the uranium in the last few years: sandstone impregnated with uranium minerals, veins of uranium-bearing materials localized in rock fractures, and 2.2-billion-year-old placer deposits, now coarse-grained sedimentary rock.

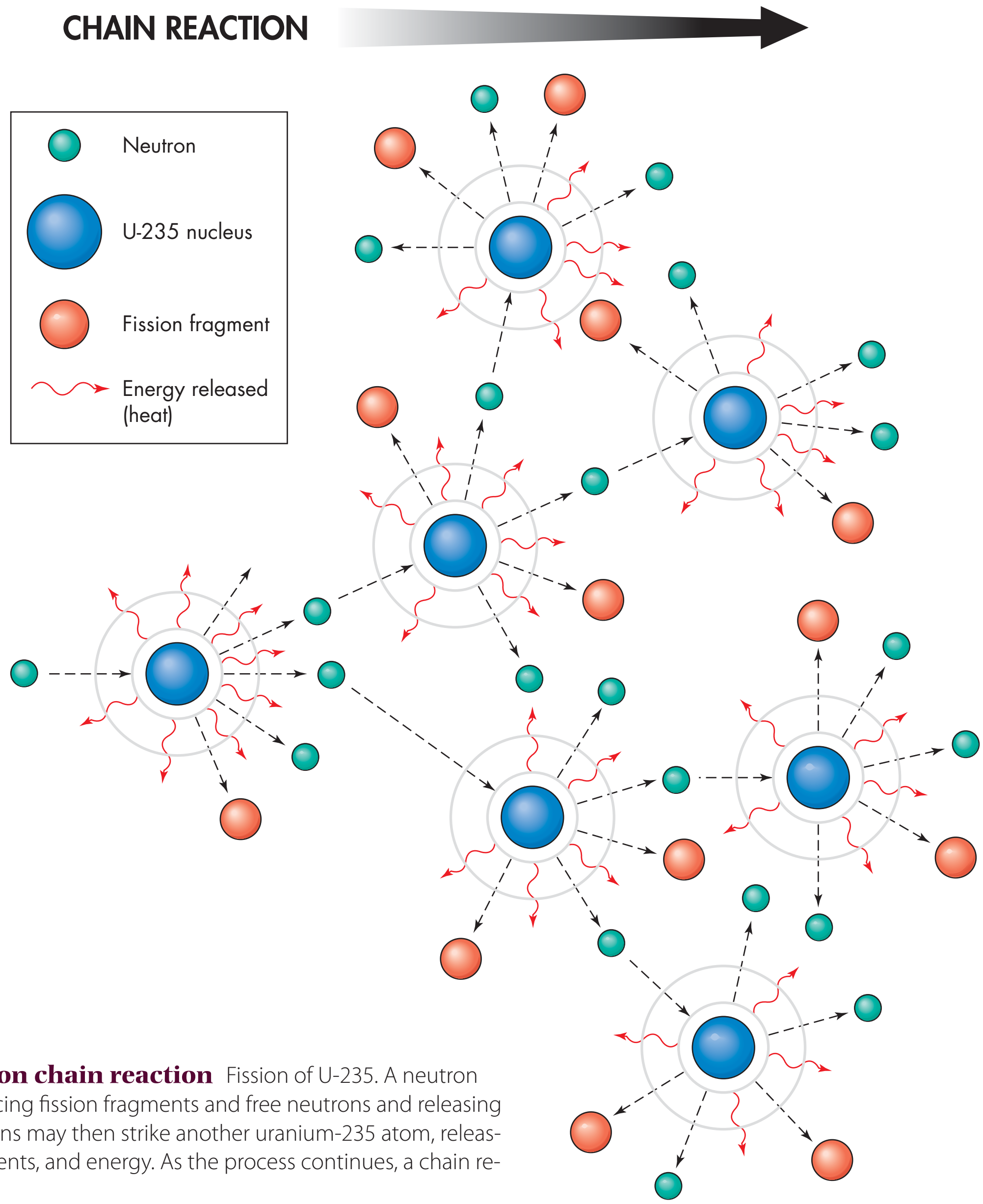


FIGURE 16.24 Nuclear fission chain reaction Fission of U-235. A neutron strikes the U-235 nucleus, producing fission fragments and free neutrons and releasing heat. Each of the released neutrons may then strike another uranium-235 atom, releasing more neutrons, fission fragments, and energy. As the process continues, a chain reaction develops.

Reactor Design and Operation

Most reactors today consume more fissionable material than they produce and are known as *burner reactors*. The reactor itself is part of the nuclear steam supply system, which produces the steam to run the turbine generators that produce electricity.

The main components of the reactor are the core, control rods, coolant, and reactor vessel. The core of the reactor, where the chain reaction takes place, is contained in a heavy stainless steel reactor vessel. For increased safety and security, the entire reactor is contained in a reinforced concrete building called a containment structure. Fuel consists of small, ceramic, enriched uranium, packed together into fuel subassemblies in the core. A stable fission chain reaction is maintained by controlling fuel concentration and the number of released neutrons that are available to cause fission. A minimum fuel concentration is necessary to keep the chain reaction self-sustaining, or *critical*; control of the number of neutrons is necessary to regulate the reaction rate. The number of neutrons is controlled by the control rods, which contain materials that capture neutrons, preventing them from bombarding other nuclei. When the rods are pulled out of the core, the

chain reaction speeds up; when they are inserted into the core, the reaction slows down.

Pumps circulate a coolant, usually water, through the reactor, extracting the heat produced by fission in the reactor. The rate of generation of heat must match the rate at which heat is carried away by the coolant. Matching the rates is usually not difficult, and reactors usually run smoothly and stably. However, the major nuclear accidents that have occurred happened when something went wrong and heat in the reactor core built up. A *meltdown* refers to a nuclear accident in which the nuclear fuel becomes so hot that it forms a molten mass. The containment of the reactor fails, and radioactivity contaminates the environment.

Other parts of the nuclear power system are the primary coolant loops and pumps, which circulate the coolant through the reactor, and heat exchangers or steam generators, which use the fission-heated coolant to make steam.

The reactor shown in Figure 16.25 is a pressurized water reactor (PWR). PWRs were initially designed in the United States, and 70 percent of U.S. nuclear reactors are PWRs. They have been modified in France and Germany to the EPR, where the E stands for European and PR means it uses pressurized water in the primary (radioactive) loop to keep the water from boiling. The EPR design has improved safety measures designed to further reduce the probability of a core meltdown; reduce the possibility of massive release of radioactivity; and, in the event of a low pressure core meltdown, limit the time and area of a massive release of radioactivity.

The first EPR reactor (1,600 MW) began in Finland in 2005. Scheduled to begin operation in 2009, it is now delayed to at least 2012. The delay, accompanied by large cost overruns related to organizational and construction problems (i.e., concrete and welding), have raised concern. However, the EPR design replaces designs that have been around for decades and adds improved safety features. Other EPRs, including some in the United States, are being planned for, as the global nuclear power industry continues to develop and grow.[30,31]

Risks Associated with Fission Reactors

Nuclear energy and the possible adverse effects associated with it have been subjects of vigorous debate. The debate is healthy because we should continue to examine the consequences of nuclear power generation very carefully.

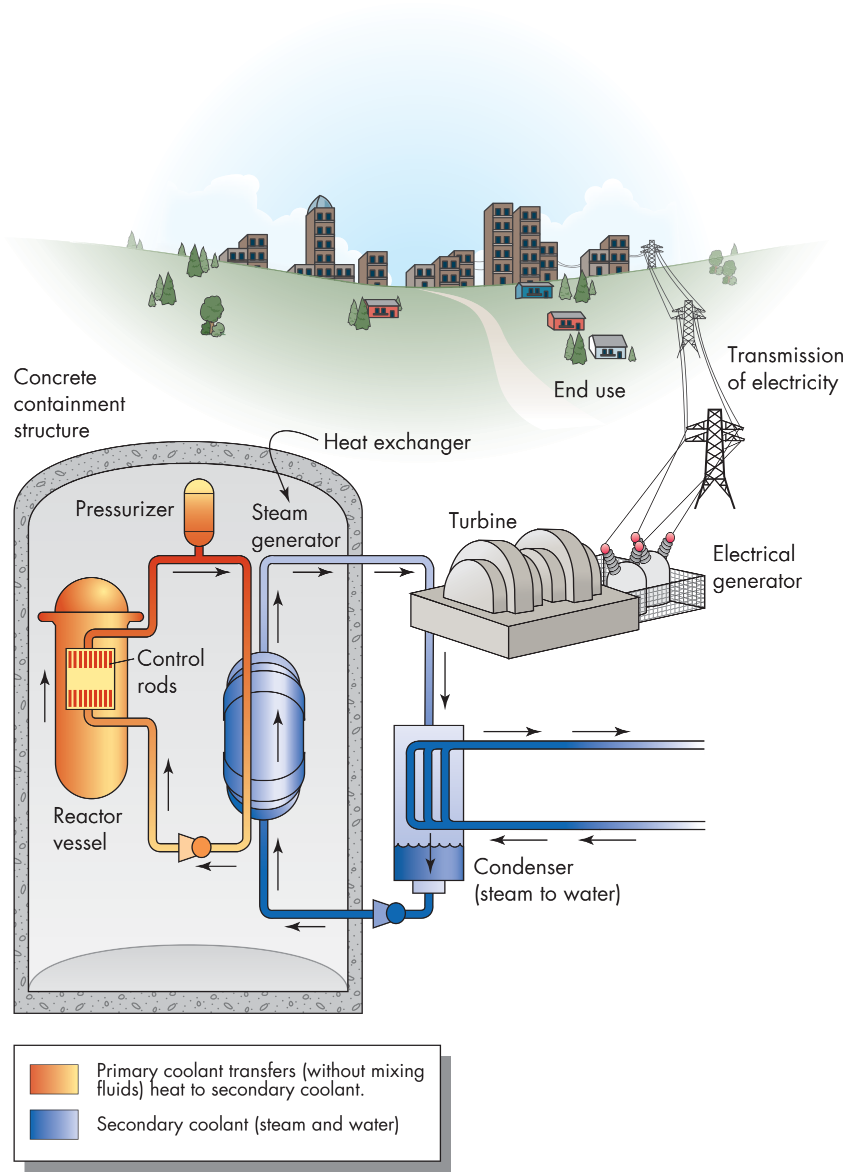


FIGURE 16.25 Pressurized water reactor Idealized diagram of a pressurized water nuclear reactor.

Nuclear fission uses and produces radioactive isotopes. Various amounts of radiation are released into the environment at every step of the nuclear cycle: mining and processing of uranium, controlled fission in reactors, reprocessing of nuclear fuel, and final disposal of the radioactive wastes. Serious hazards are associated with transporting and disposing of nuclear material, as well as with supplying other nations with reactors. Furthermore, since the plutonium produced by nuclear reactors can be used to make nuclear weapons, terrorist activity and the possibility of irresponsible actions by governments add a risk that is present in no other form of energy production.

An uncontrolled chain reaction—a nuclear explosion—cannot occur in a nuclear reactor because the fissionable material is not used in the concentrated form necessary for an explosion. However, unwanted chemical reactions in a reactor can produce explosions that release radioactive substances into the environment. Although the chance of a disastrous accident is estimated to be very low, it increases with every reactor put into operation. Major accidents have already occurred, including Three Mile Island near Harrisburg, Pennsylvania, in 1979, and the disastrous accident at Chernobyl in the former Soviet Union, now Ukraine, in 1986.

Three Mile Island. One of the most serious events in the history of U.S. nuclear power occurred on March 28, 1979, at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania. The malfunction of a valve and human errors at the nuclear plant resulted in a partial core meltdown, with the release of radioisotopes into the environment. Although intense radiation was released into the interior of the containment structure, it functioned as designed, and only a relatively small amount of radiation was released into the environment.

The Three Mile Island incident clearly demonstrated that there are potential problems with nuclear power. Historically, nuclear power had been relatively safe, and the state of Pennsylvania was unprepared for the accident. One of the serious impacts of the incident was fear, but, surprisingly, no staff member from the Department of Health was allowed to sit in on briefing sessions.

Because the long-term chronic effects of exposure to low levels of radiation are not well understood, the effects of Three Mile Island exposure, although apparently small, are not easy to estimate. Furthermore, the Three Mile Island accident illustrates that our society needs to improve the way in which it handles crises arising from the release of pollutants created by our modern technologies.[32]

Chernobyl. Lack of preparedness was dramatically illustrated by events that started on the morning of Monday, April 28, 1986. Workers at a nuclear facility in Sweden, frantically searching for the source of elevated levels of radiation near their power plant, concluded that it was not their facility that was leaking radiation but that the radioactivity was coming from the Soviet Union, by way of prevailing winds. Confronted, the Soviets admitted that there had been an accident at their nuclear power plant at Chernobyl on April 26. This was the first notice that the world's worst accident in the history of nuclear power had occurred.

It is believed that the system that supplies cooling waters for the Chernobyl reactor failed as a result of human error. This caused the temperature of the reactor core to rise to over 3,000°C (about 5,400°F), melting the uranium fuel. Explosions blew off the top of the building over the reactor, and the graphite surrounding the fuel rods ignited. The fires produced a cloud of radioactive particles that rose high into the atmosphere. There were 237 confirmed cases of acute radiation sickness, and 31 people died of radiation sickness.[33] In the days following the accident, about 3 billion people in the Northern Hemisphere received varying amounts of radiation from Chernobyl. With the exception of the 30 km (19 mi) zone surrounding Chernobyl, the human exposure was relatively small. In Europe, where exposure was highest, it was less than the amount of natural radiation received over the course of 1 year.[33]

Approximately 115,000 people in that 30 km (19 mi) zone were evacuated, and as many as 24,000 people were estimated to have received an average radiation dosage several hundred times higher than a natural annual exposure. This group of people is being studied carefully. Studies have found that the annual number of childhood thyroid cancer cases has risen steadily in the three countries of Belarus, Ukraine, and the Russian Federation (those most affected by Chernobyl) since the accident. In 1994, there were 132 new thyroid cancer cases, and, since the accident, a total of 653 thyroid cancer cases have been diagnosed in children and adolescents. These cancer cases are thought to be linked to the

accident, although other factors, including environmental pollution, may also play a role. It is predicted that a few percent of the 1 million children exposed to the radiation eventually will contract thyroid cancer.[34] Outside the 30 km (19 mi) zone, the increased risk of contracting cancer is small. However, one estimate is that, over the next 50 years, Chernobyl will have been responsible for approximately 16,000 deaths worldwide.

In the area surrounding Chernobyl, radioactive materials continue to contaminate soils, vegetation, surface water, and groundwater, presenting a hazard to plants and animals. The evacuation zone may be uninhabitable for a very long time unless a way is found to remove the radioactivity.[33] Estimates of the total cost of the Chernobyl accident vary widely but will probably exceed $200 billion.

Although the Soviets were accused of not paying sufficient attention to reactor safety and of using outdated equipment, people are still wondering if such an accident could happen again elsewhere. Because there are several hundred reactors producing power in the world today, the answer is yes. The Chernobyl accident follows a history of about 10 accidents that released radioactive particles between 1967 and 2001. Therefore, although Chernobyl is the most serious nuclear accident to date, it certainly was not the first and is not likely to be the last. As a result of the Chernobyl accident, risk analysis in nuclear power is now a real-life experience rather than a computer simulation.

Chernobyl was finally shut down on December 15, 2000, when reactor no. 3 was switched off, 14 years after the accident in reactor no. 4. Reactor no. 2 was closed in 1991 after a fire, and no. 1 was shut down in 1996. The closure occurred as a result of international pressure, with the West agreeing to pay for cleanup work and to construct two new nuclear power plants at other sites in the Ukraine.

The area around the accident may not be safe for hundreds of years. The city of Prypyat, 5 km (3 mi) from Chernobyl, is a "ghost city." At the time of the accident, the population of Prypyat was 48,000. Today, the town is abandoned, with blocks of vacant apartment buildings and rusting vehicles. The roads are cracking, and trees and other vegetation are transforming the once-urban land back to green fields. Prypyat was evacuated within 2 days of the accident. This was just 3 days before May Day, which was the celebration of Soviet power. Today, cases of thyroid cancer are still increasing. The final impact of the world's most serious nuclear accident has yet to completely unfold.[35] So far, the number of deaths has been less than expected, but the contamination is more widespread than expected.

The Future of Energy from Fission

Nuclear power produces about 20 percent of the electricity in the United States today. About 104 reactors are now in operation, more than 80 percent of which are in the eastern United States. The states with the largest percentage of electricity produced from nuclear power plants are Vermont (74 percent), South Carolina (57 percent), New Jersey (51 percent), and Connecticut (49 percent). Many more reactors are needed to realize uranium's potential energy contribution.[36]

The United States has recently suggested, as national policy, that nuclear power should be expanded in the future. Evidently, more Americans agree with this suggestion than in previous years; however, there remains significant opposition to the idea.[36,37]

Nuclear fission may, indeed, be one of the answers to our energy problems. Its use is being seriously evaluated for future increase because it is an alternative to fossil fuels that does not release carbon dioxide into the atmosphere (and, thus, it does not contribute to global warming) and it does not release pollutants that cause acid rain. However, with the use of nuclear power comes the responsibility of ensuring that it will be used for people, not against them, and that future generations will inherit a quality environment, free from worry about hazardous nuclear waste.[38]

Radioactive Waste Management

Radioactive waste management, the safe disposal of radioactive waste, is a significant environmental issue facing the United States and the rest of the world. Radioactive wastes are by-products that must be expected when electricity is produced from nuclear reactors or weapons are produced from plutonium. Radioactive waste may be grouped into three general categories: low-level waste, transuranic waste, and high-level waste.

Low-Level Radioactive Wastes. *Low-level radioactive wastes* contain only small amounts of radioactive substances. Low-level wastes include a wide variety of

items, such as residues or solutions from chemical processing; solid or liquid plant waste, sludges, and acids; and slightly contaminated equipment, tools, plastic, glass, wood, fabric, and other materials.[39] Before disposal, liquid low-level radioactive waste is solidified or packaged with material capable of absorbing at least twice the volume of liquid present.[40]

Radioactive decay of low-level waste does not generate a great deal of heat, and a general rule is that the material must be isolated from the environment for about 500 years to ensure that the level of radioactivity does not produce a hazard. In the United States, the philosophy for management of low-level waste has been "dilute and disperse." Experience suggests that low-level radioactive waste can be buried safely in carefully controlled and monitored near-surface burial areas in which the hydrologic and geologic conditions severely limit the migration of radioactivity.[37] Such waste has been buried at several sites in states including Washington, Nevada, New Mexico, Missouri, Illinois, Ohio, Tennessee, Kentucky, South Carolina, and New York.

Despite precautions, several of the burial sites for low-level radioactive waste, including those in Tennessee and Washington, have not provided adequate protection of the environment. This failure has been due, at least in part, to a poor understanding of the local hydrologic and geologic environment. For example, a study of the Oak Ridge National Laboratory in Tennessee suggests that, in places, the water table is less than 7 m (23 ft) below the ground surface. The investigation identified migration of radioactive materials from one of the burial sites and concluded that containment of the waste in that area is difficult because of the short residence time of water in the vadose zone. In other words, liquid radioactive materials released from the disposal sites do not take long to infiltrate the vadose zone and percolate down to the groundwater.[40] However, near Beatty, Nevada, the depth to the water table is approximately 100 m (300 ft). The low-level radioactive waste-disposal facility there has apparently been successful in its containment of radioactive waste. Its success is based partly on the long length of time needed for any pollutants generated to enter the groundwater environment.[40]

Transuranic Waste. *Transuranic waste* is nuclear waste composed of human-made radioactive elements heavier than uranium. Most transuranic waste is industrial trash, such as clothing, rags, tools, and equipment that has been contaminated. Although the waste is low level in terms of intensity of radioactivity, plutonium has a long half-life (i.e., the time required for the radioactivity to be reduced to one-half its original level) and requires isolation from the environment for about 250,000 years. Most transuranic waste is from the production of nuclear weapons and from cleanup of former nuclear weapons facilities. As of 1999, these wastes were being transported to a disposal site near Carlsbad, New Mexico. The waste is isolated at a depth of 655 m (2,150 ft) in saltbeds that are several hundred meters thick (**Figure 16.26**). Rock salt at the New Mexico site has several advantages:[41,42]

- The salt is about 225 million years old, and the area is geologically stable, with very little earthquake activity.
- The salt is easy to mine and has no flowing groundwater. Rooms excavated in the salt that are about 10 m (33 ft) wide and 4 m (13 ft) high are used for disposal.
- The rock salt flows slowly into mined openings. As a result, the slow-flowing salt will naturally close the waste-filled spaces in the storage facility in 100 to 200 years, sealing the waste.

The New Mexico disposal site is important because it is the first geologic disposal site for nuclear waste in the United States. It is a pilot project that is being evaluated very carefully. Safety is the main concern. Procedures to transport the waste, as safely as possible, to the disposal site and place it underground in the disposal facility have been established. The waste will be hazardous for many thousands of years; therefore, there are uncertainties concerning future languages and cultures at the site. Clear warnings above and below ground have been created, and the site is clearly marked to help ensure that human intrusion will not occur in the future.[40]

High-Level Radioactive Wastes. *High-level radioactive wastes* are produced as fuel assemblages in nuclear reactors become contaminated or clogged with large quantities of fission products. This spent fuel must periodically be removed and reprocessed or disposed of. Fuel assemblies will probably not be

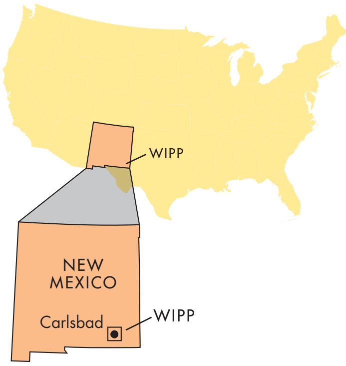
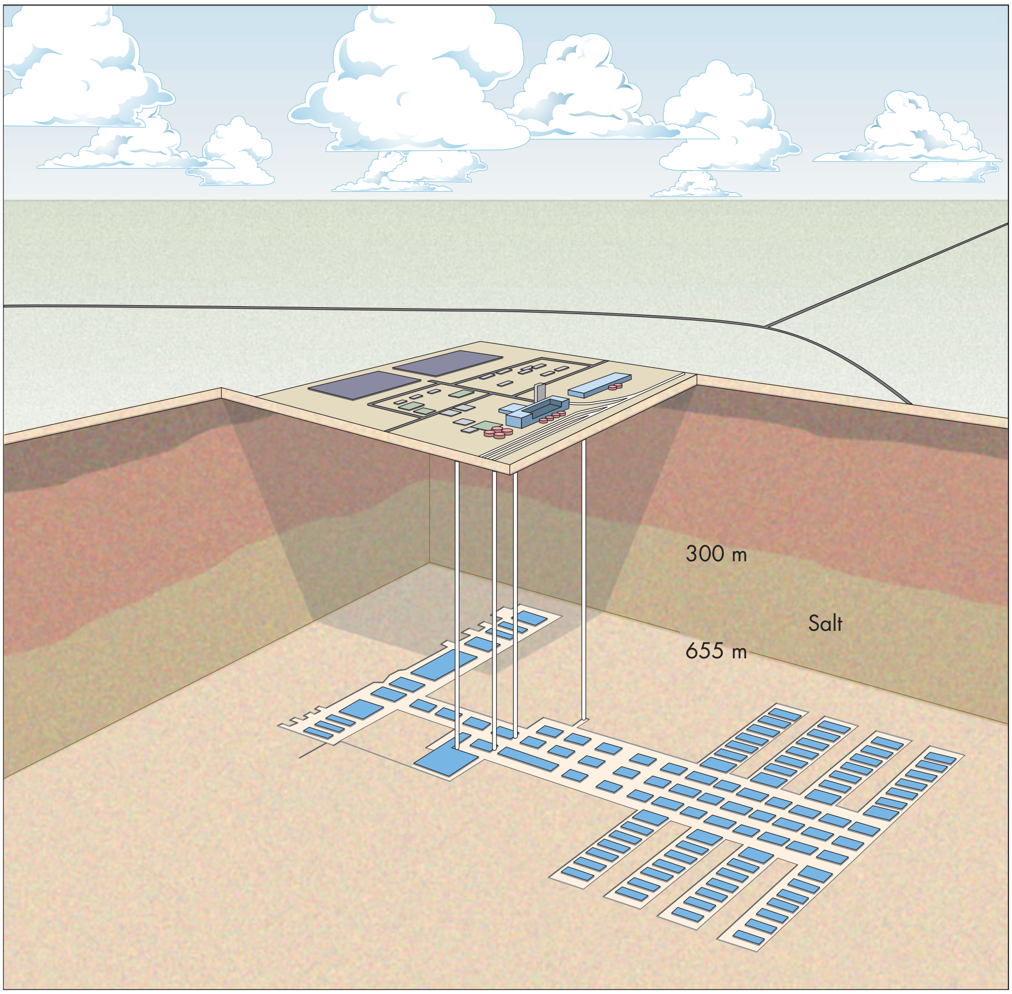


FIGURE 16.26 New Mexico nuclear waste disposal facility Idealized diagram of a waste isolation pilot plant (WIPP) disposal site in New Mexico for transuranic nuclear waste. *(U.S. Department of Energy)*



reprocessed in the near future in the United States because reprocessing is more expensive than mining and processing new uranium; therefore, the present waste-management problems involve removal, transport, storage, and eventual disposal of spent fuel assemblies. Today, spent nuclear fuel in the United States is stored in steel-lined concrete containers at nuclear power plants.

The Scope of the High-Level Disposal Problem. Hazardous radioactive materials produced from nuclear reactors include fission products, such as

krypton-85, strontium-90, and cesium-137. Each of these radioactive elements has a different half-life. One of the biggest challenges faced in managing radioactive waste disposal is the various half-lives associated with fission products. In general, at least 10 half-lives, and preferably more, are required before a material is no longer considered a health hazard. Therefore, a mixture of the fission products mentioned above would require hundreds of years of confinement from the biosphere. Reactors also produce a small amount of plutonium-239 (with a half-life of 24,000 years), which is a human-produced isotope that does not occur naturally. Because plutonium and its fission products must be isolated from the biological environment for a quarter of a million years or more, their permanent disposal is a geologic problem.

Disposal of High-Level Waste in the Geologic Environment. There is fair agreement that the geologic environment can provide the most certain safe containment of high-level radioactive waste. The Nuclear Waste Policy Act of 1982 initiated a comprehensive federal and state program for the disposal of high-level nuclear waste. The Department of Energy was responsible for investigating several potential sites, and the act originally called for the president to recommend a site by 1987. In December 1987, Congress amended the act to specify that only the Yucca Mountain site in southern Nevada would be evaluated to determine whether high-level radioactive waste could be disposed of there. Some scientists and others believe that the site was chosen not so much for its geology, although the rock type at the site does have several favorable qualities for disposal, but because it is an existing nuclear reservation and, therefore, might draw minimal social and political opposition.[43] However, opposition has been intense and, apparently, successful. It now appears that, after billions of dollars have been spent, Yucca Mountain is not to be the site where nuclear waste will be soon, if ever, disposed of. Nevertheless, the geology of the site is worthy of discussion.

The rock at the Yucca Mountain site is densely compacted *tuff*, a rock composed of compacted volcanic ash. Precipitation is about 15 cm (6 in.) per year, and most of this runs off or evaporates. The depth to a potential repository is about 300 m (984 ft) below the mountain's surface, and such a repository could be constructed well above the water table. The Department of Energy and the U.S. Geological Survey have completed an extensive scientific evaluation of the Yucca Mountain site. The study has helped determine how well the geologic and hydrologic setting can isolate high-level nuclear waste from the environment.[44]

Long-Term Safety. A major problem with the disposal of high-level radioactive waste remains: How credible are long-range geologic predictions—that is, predictions of conditions thousands to millions of years in the future?[45] There is no easy answer to this question because geologic processes vary over both time and space. Climates change over long periods of time, as do areas of erosion, deposition, and groundwater activity. For example, large earthquakes, occurring hundreds or even thousands of kilometers from a site, may permanently change groundwater levels. The known seismic record for the western United States dates back only 100 years; estimates of future earthquake activity are tenuous at best. Ultimately, geologists can evaluate the relative stability of the geologic past, but they cannot guarantee future stability. Therefore, decision makers, and not geologists, need to evaluate the uncertainty of prediction in light of pressing political, economic, and social concerns.[45] These problems do not mean that the geologic environment is not suitable for safe containment of high-level radioactive waste, but care must be taken to ensure that the best possible decisions are made on this critical and controversial issue.

Energy from Fusion

In contrast to nuclear fission, *nuclear fusion* combines the nuclei of lighter elements to produce heavier ones. The process of nuclear fusion releases energy and is the source of energy in our Sun and other stars. Harnessing nuclear fusion is a research objective that has met with some success, but it is not yet certain whether commercial fusion power plants can be constructed that are economically competitive with other energy sources. From an environmental view, fusion appears attractive because little radioactive waste is produced and mining and transportation impacts are small, compared with those for fossil fuels and nuclear fission. The fuel for fusion is hydrogen, the supply of which is nearly

unlimited and, as a result, fusion has the potential of being a nearly unlimited source of energy for the future. However, we do not yet have the technology to harness the hydrogen for our energy needs.[8]

16.8 Geothermal Energy

The use of **geothermal energy**—natural heat from Earth's interior—is an exciting application of geologic knowledge and engineering technology. The idea of harnessing Earth's internal heat is not new: Geothermal power was developed in Italy, using dry steam, in 1904 and is now used to generate electricity at numerous sites around the world, including a few in the western United States and Hawaii. At many other sites, geothermal energy that is not hot enough to produce electrical power is used to heat buildings or for industrial purposes. Existing geothermal facilities use only a small portion of the total energy that might eventually be tapped from Earth's reservoir of internal heat; the geothermal resource is vast. If only 1 percent of the geothermal energy in the upper 10 km (6.2 mi) of Earth's crust could be captured, it would amount to 500 times the total global oil and natural gas resource.[46]

Geology of Geothermal Energy

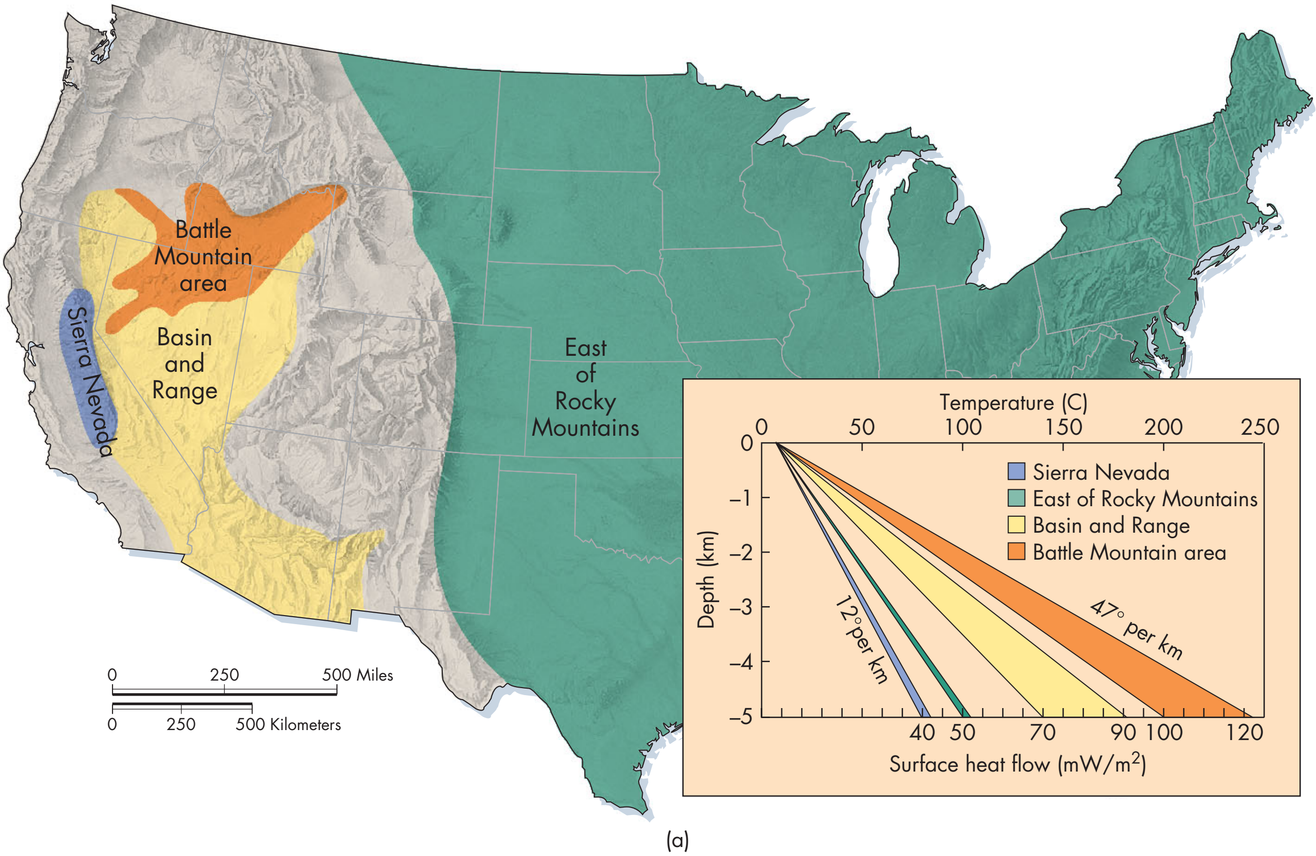
Natural heat production within Earth is only partially understood. We know that some areas have a higher flow of heat from below than others and that, for the most part, these locations are associated with tectonic processes. Divergent and convergent plate boundaries are areas where this natural heat flow from Earth is anomalously high. The coincidence of geothermal power plant locations and areas of known active volcanism is no accident.

Temperature increases with depth below Earth's surface; it is measured in degrees per kilometer and is referred to as the *geothermal gradient*. In the United States, the geothermal gradient varies from about 12°C to 47°C (53°F to 116°F) per kilometer (0.6 mi) (**Figure 16.27**). In general, the steeper the gradient, the greater the heat flow to the surface. A steep geothermal gradient indicates that hot rock is closer to the surface than usual. A moderate gradient of 30°C to 45°C (86°F to 113°F) per kilometer is found over vast areas in the western U.S. Basin and Range, especially in the Battle Mountain region (Figure 16.27a). This area, with some exceptions, is clearly a good prospect for geothermal exploration. Figure 16.27b shows heat flow for the western United States, along with locations of existing geothermal power plants. Total power production is about 3,000 MW, more than 90 percent of which is in California. About one-third of total production is in the Geysers facility, 145 km (90 mi) north of San Francisco, California, where electrical energy has been produced from steam for many years (G on Figure 16.27, and see **Figure 16.28**, page 573). A typical commercial geothermal well will produce between 5 and 8 MW of electrical power.[46] (Remember: 1 watt = 1 joule per second. See A Closer Look: Energy Units.)

Several geothermal systems may be defined on the basis of geologic criteria. Each system has a different origin and different potential as an energy source.

Hydrothermal Convection Systems. Hydrothermal convection systems are characterized by a geothermal basin in which a variable amount of hot water circulates. There are two basic types: vapor-dominated systems and hot-water systems. Vapor-dominated hydrothermal convection systems are geothermal reservoirs in which both water and steam are present (**Figure 16.29**, page 573). Near the surface, the pressure is lower than at deeper levels, and water changes quickly to superheated steam, which can be tapped and piped directly into turbines to produce electricity. These systems characteristically have a slow recharge of groundwater, meaning that the hot rocks boil off more water than can be replaced in the same amount of time by natural recharge or by injection of water from a condenser after power generation. Vapor-dominated systems are not very common. Only three have been identified in the United States: the Geysers, California; Mt. Lassen National Park, California; and Yellowstone National Park, Wyoming.[46]

In the United States, hot-water hydrothermal convection systems are about 20 times more common than vapor-dominated systems. Hot-water systems, with temperatures greater than 150°C (300°F), have a zone of circulating hot water that, when tapped, moves up to a zone of reduced pressure, yielding a mixture of steam and water at the surface. The water must be removed from the steam before the steam can be used to drive the turbine.[46]



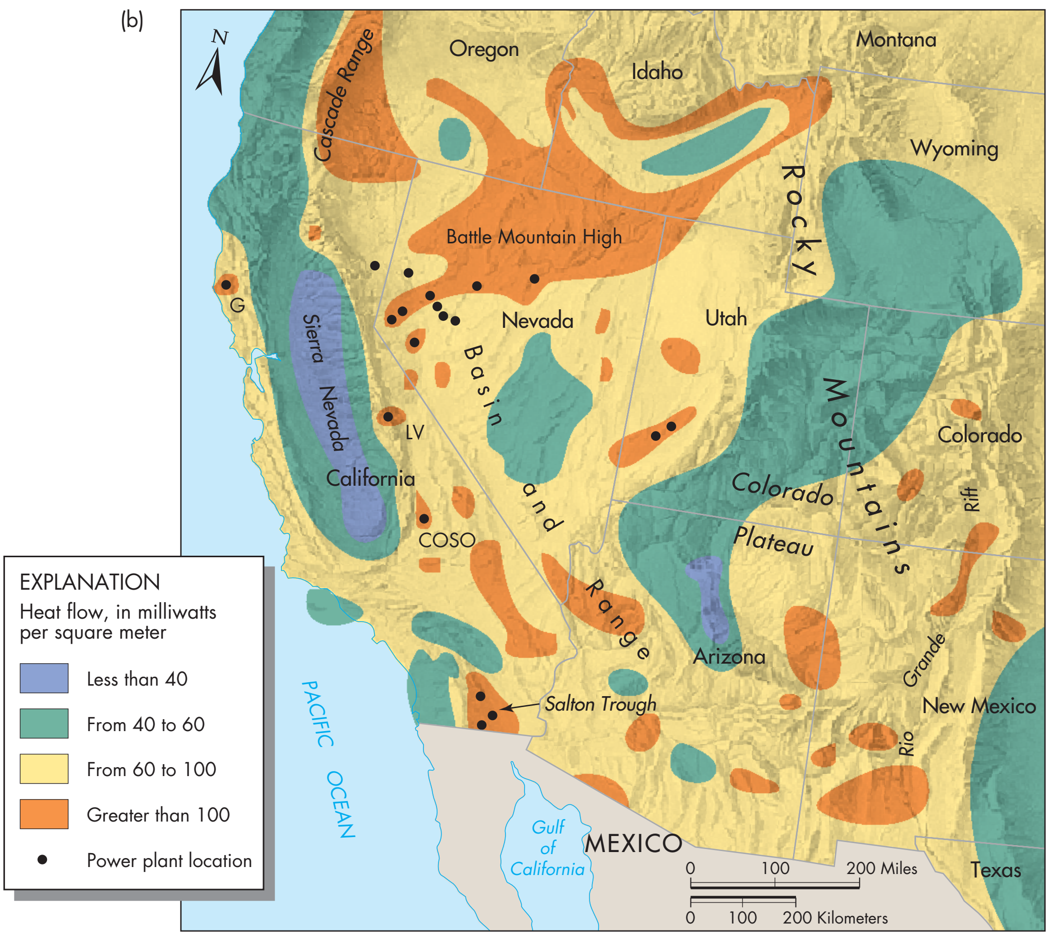


FIGURE 16.27 Heat flow in the United States (a) Geothermal gradients (12° to 47°C per km [53° to 116°F per 0.6 mi]) and generalized heat flow in the United States. (b) A more detailed map of heat flow for the western United States and the locations of geothermal power plants. One milliwatt per square meter is equivalent to 10,000 watts per square kilometer. *(From Duffield, W. A. and Sass, J. H. 2003. Geothermal Energy—Clean Power from Earth's Heat.* U.S. Geological Survey Circular 1249*)*

FIGURE 16.28 Geothermal power plant Aerial view of the Geysers power plant north of San Francisco, California. The facility is the world's largest geothermal electricity development. *(Courtesy of Pacific Gas and Electricity)*

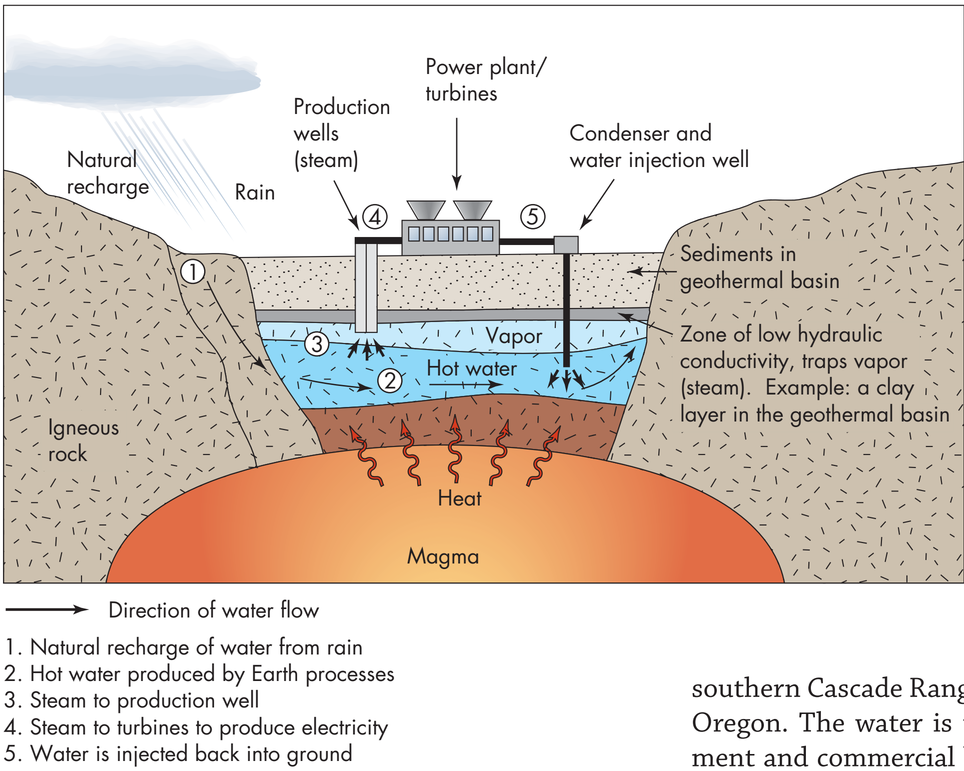


FIGURE 16.29 Vapor-dominated geothermal system and power plant Idealized diagram of a vapor-dominated geothermal system. Wells produce steam that runs turbines to make electricity.

As shown in **Figure 16.30**, the water can be injected back into the reservoir to be reheated.

Hot water from geothermal sources has a number of potential direct uses. For example, Iceland uses hot water for space heating and industrial processes. Abundant near-surface, hot geothermal water in the southern Cascade Ranges occurs near Klamath Falls, Oregon. The water is used to heat homes, government and commercial buildings, dairies, fish farms, and greenhouses. Geothermal heat from 60° to 80°C water is used in southwestern France (Paris region) to heat about 200,000 apartments, as well as to heat water for domestic uses.[46]

Groundwater Systems. The idea of using groundwater at normal shallow underground temperatures is a relatively new one. At a depth of about 100 m

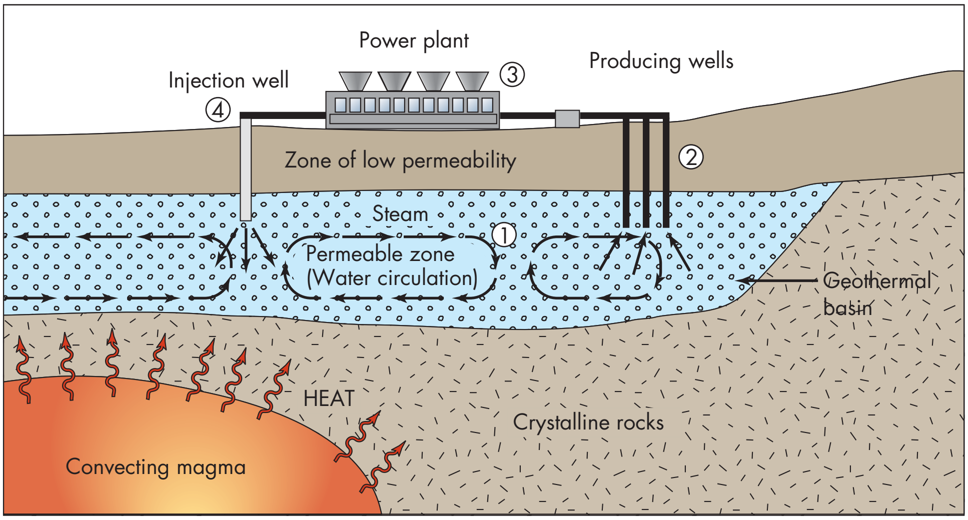


FIGURE 16.30 A hot-water geothermal system At the power plant, the steam is separated from the water and used to generate electrical power. The water is injected back into the geothermal system through a disposal well. *(Courtesy of Pacific Gas and Electricity)*

(328 ft), groundwater typically has a temperature of about 13°C (55°F). This is cold, if you want to use it for a bath, but it is warm compared with winter air temperature in the eastern United States. Compared with summer temperatures, it is cool. Heat pumps, devices that can raise or lower the temperature of air or water, can use these temperature differences to heat buildings in the winter and cool them in the summer by transferring heat between groundwater and the air in a building. Although initially expensive because of well drilling, geothermal systems using constant-temperature groundwater are in service in numerous midwestern and eastern U.S. locations. The technology for these systems is well known, and the equipment is easily obtained. As energy costs increase, such systems are becoming even more attractive.

Environmental Impact of Geothermal Energy Development

The adverse environmental impact of intensive geothermal energy development is much less severe than that of other energy sources, but it is nonetheless considerable. Environmental problems associated with geothermal energy include on-site noise, gas emissions, and scars on the land. Fortunately, development of geothermal energy does not require the extensive transportation of raw materials or refining that is typical of the development of fossil fuels. Geothermal plants generate less than 1 percent of the nitrogen oxides and only 5 percent of the carbon dioxide created by coal-burning power plants producing comparable amounts of power.[46] Finally, geothermal energy does not produce the atmospheric particulate pollutants associated with burning fossil fuels or radioactive waste.

Geothermal energy production does have associated hazards. With the exception of vapor-dominated systems, geothermal development produces considerable thermal pollution from hot wastewaters. The wastewaters can be saline, mineralized, or highly corrosive to pipes, pumps, and other equipment. The plan is to dispose of these waters by reinjecting them into the geothermal reservoir. Finally, geothermal energy development may adversely affect nearby geyser activity by reducing or changing the heat source driving the geysers. As a result, federal legislation has been passed to protect the geysers, including the famous geyser Old Faithful and hot springs of Yellowstone National Park, by prohibiting geothermal development in national parks. What is not known is what constitutes adequate protection. How large a buffer zone is necessary to ensure that geothermal development outside the park boundary does not damage Yellowstone's geysers and hot springs?

Future of Geothermal Energy

Geothermal energy is a viable site-specific energy source. The estimated yield from a small portion of this vast resource could far exceed that of hundreds of modern nuclear power plants. The cost to produce electricity from many geothermal fields is comparable to the costs of other sources, such as wind and natural gas.

At present, geothermal energy supplies only a small fraction of 1 percent of the electrical energy produced in the United States. The total output from geothermal sources is not likely to exceed a few percent—10 percent at most—of electrical output in the near future. This outlook is true even for California, where geothermal energy has been produced and where expanding facilities are likely. At present, geothermal energy supplies about 6 percent of California's electricity. Nevertheless, the growth in power produced from geothermal sources has increased dramatically in the past few decades, and this trend will continue.[46]

16.9 Renewable Energy Sources

Fossil fuels are the main energy sources used today; they supply approximately 90 percent of the global energy consumed by people. All other sources are designated **alternative energy** and are subdivided into two groups: *renewable energy* and *nonrenewable energy*. Nonrenewable alternative energy sources include nuclear energy and geothermal energy, which were discussed previously. The renewable sources are solar power, water or hydropower, hydrogen, wind power, and energy derived from biomass.

Use of alternative sources, particularly solar and wind power, is growing at tremendous rates. Alternative energy sources have proven to be competitive with coal burning, but they do not pollute our urban air, cause acid rain, or warm our climate to an unacceptable level. Alternative renewable energy sources, such as solar and wind power, do not cause rapid or other climate change. Solar and wind power do not alter weather to produce killer storms or droughts; nor do they raise sea levels around the world, increasing coastal erosion and threatening low-lying areas, including islands. Alternative, renewable energy sources offer our best chance to break our addiction to fossil fuels and develop a sustainable energy policy that will not harm Earth.[47,48]

A primary directive to ensure the success of alternative energy is to match renewable energy sources to sites where the natural resources for that source are of the highest quality. For instance, site solar energy power plants in the southwestern United States, where sunlight is most intense; site wind farms in the Great Plains, Texas, the Northeast, and California, where the strength of wind is strong and steady; and use biomass at existing coal-burning power plants in locations where forest and agriculture fuel resources are abundant.[49]

Renewable energy sources are usually discussed as a group because they are derivatives of the Sun's energy. That is, **solar energy**, broadly defined, comprises many of the renewable energy sources, as shown in **Figure 16.31**. They are renewable because they are regenerated by the Sun within a time period that is useful to people. Renewable energy sources have the advantage of being inexhaustible and are often associated with minimal environmental degradation. With the exception of burning biomass or its derivative, urban waste, solar energy does not entail fuel burning and, therefore, does not pose a threat of increasing atmospheric carbon dioxide and modifying the climate. Another important aspect of renewable sources is that the lead time necessary to implement the technology is often short, relative to the development of new sources or the construction of power plants that utilize fossil or nuclear fuels.

The total amount of solar energy reaching Earth's surface is huge. On a global scale, 10 weeks of solar energy is roughly equivalent to the energy stored in all known reserves of coal, oil, and natural gas on Earth. The average global recoverable solar power resource is about 80 times the power now used by people on Earth.

Solar Energy

Solar energy is used directly through passive solar systems or active solar systems. *Passive* solar energy systems involve architectural design that enhances absorption of solar energy and takes advantage of the natural changes in solar energy that occur throughout the year without requiring mechanical power. A simple technique is to design overhangs on buildings that block high-angle summer sunlight but allow low-angle winter sunlight to penetrate and warm rooms. Another method is to build a wall that absorbs solar energy and emits it into a room, thus

warming it. Numerous homes and other buildings in the southwestern United States, as well as other parts of the country, now use passive solar systems for at least part of their energy needs.[49] *Active* solar energy systems require mechanical power, usually pumps and other apparatuses, to circulate air, water, or other fluids from solar collectors to a heat sink, where the heat is stored until used.

Solar Collectors. Solar collectors are usually flat panels, consisting of a glass plate over a black background where water is circulated through tubes. Solar radiation enters the glass and is absorbed by the black background, heating the water in the circulating tubes to 38° to 93°C (100° to 200°F).[50] The number of systems using these collectors in the United States continues to grow.

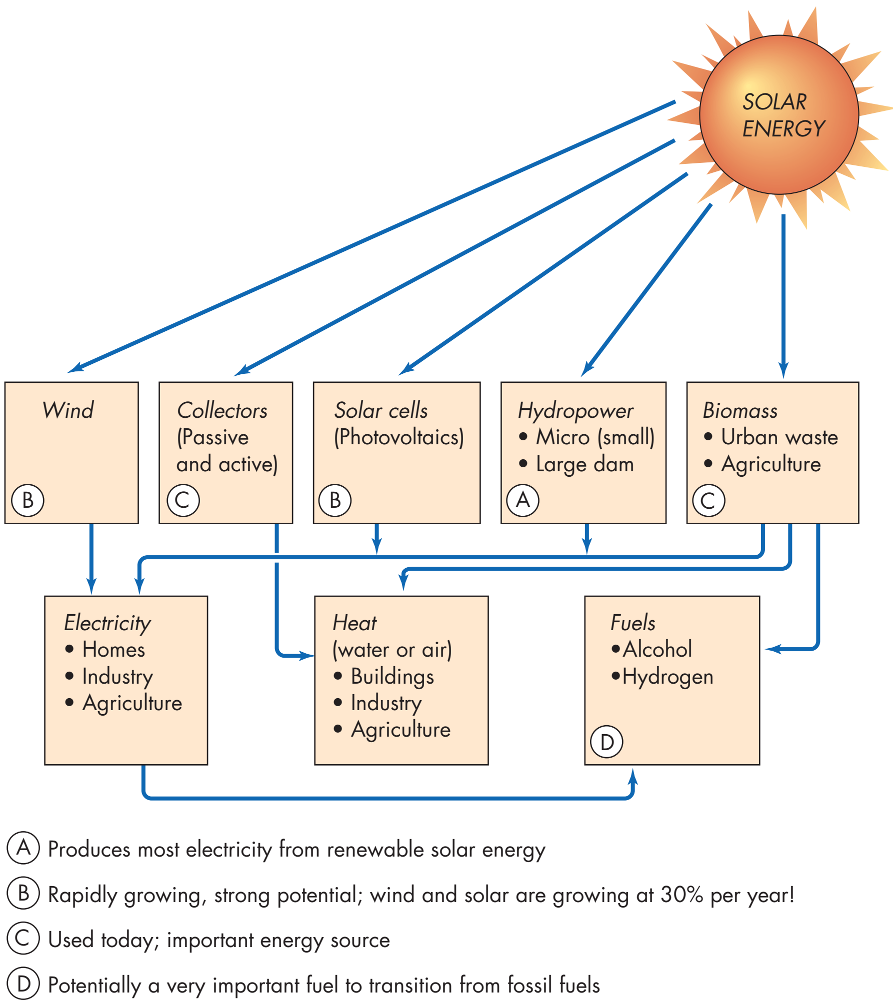


FIGURE 16.31 Types of renewable solar energy Selected examples, with growth and potential.

Photovoltaics. The technology that converts sunlight directly into electricity, using a solid semiconductor material, is known as *photovoltaics*. Photovoltaics, at a growth rate of 35 percent per year, is the most rapidly growing source of energy in the world today. The systems use photovoltaic, or solar, cells made of silicon or other materials and solid-state electronic components with few or no moving parts. The cells are constructed in standardized modules, which can be combined to produce systems of various sizes. As a result, power output can be matched to the intended use. Electricity is produced when sunlight strikes a cell, causing electrons to flow out of the cell through electrical wires.

Photovoltaics are emerging as a significant energy source in developing countries that, with relatively poor economies, do not have the financial ability to build large central power plants that burn fossil fuels. We now recognize that solar technology is simple and relatively inexpensive; it is also capable of meeting energy uses for people in most places in the world. One solar company in the United States is equipping villages in several countries with photovoltaic systems that power lights and televisions at an installed cost of a few hundred dollars per household.[51] Solar roofing tiles allow the roof of a building to become its own power plant.[52] Panels of solar cells can also be placed on a building's roof, walls, or window glass.[49]

Although there are specific instances in which the cost of using photovoltaics is comparable to that of using grid-connected power, photovoltaics are still considerably more expensive than conventional energy sources. However, the gap is slowly narrowing.[47,53,54]

Solar Energy and the Environment. The use of solar energy has a relatively low impact on the environment. The major disadvantage is that solar energy is relatively dispersed; a large land area is required to generate a large amount of energy. This problem is negligible when solar collectors can be

combined with existing structures, as, for example, the addition of solar water heaters on roofs of existing buildings. The impact of solar energy systems can be minimized by locating centralized systems in areas not used for other purposes and by making use of dispersed solar energy collectors on existing structures wherever possible.

Hydrogen

Hydrogen is the fuel burned by our Sun. It is the lightest, most abundant element in the universe. Hydrogen gas may be the fuel of the future and the key to clean energy. Hydrogen is a high-quality fuel that can be easily used in any of the ways in which we normally use fossil fuels, such as to power automobile and truck engines or to heat water or buildings. When used in **fuel cells**, similar to batteries, hydrogen can produce electricity. Hydrogen, like natural gas, can be transported in pipelines and stored in tanks, and it can be produced by using solar and other renewable energy sources to split water into oxygen and hydrogen. Hydrogen is a clean fuel; the combustion product of burning hydrogen is water, so it does not contribute to global warming, air pollution, or acid rain. It is expected that experimentation with hydrogen will continue and that the fuel produced may be substantially reduced in price in the future. Hawaii, which imports oil for 88 percent of its energy needs, has abundant geothermal, solar, and wind sources that could be used to produce hydrogen. Hawaii eventually hopes to be a net exporter of energy in the form of hydrogen. Iceland, at the end of the twentieth century, announced that it intends to be the first hydrogen society, planning to export hydrogen to Europe by 2050.[55–57]

Water Power

Water power is an ancient source of energy. Water has been successfully used as a source of power at least since the time of the Roman Empire. Waterwheels were turning in Western Europe in the seventeenth century, harnessing the energy of moving water and converting it to mechanical energy. During the eighteenth and nineteenth centuries, large waterwheels provided the energy to power grain mills, sawmills, and other machinery in the United States.

Hydroelectric Power. Today, hydroelectric power plants provide about 10 percent of the total electricity produced in the United States. Although the total amount of electrical power produced by running water will increase somewhat in the coming years, the percentage may be reduced as the production of other energy sources, such as nuclear, wind, solar, and geothermal, increase more quickly.

Most of the acceptable sites for large dams to produce hydropower are already being utilized. However, small-scale hydropower systems may be more common in the future. These are systems designed for individual homes, farms, or small industries. They will typically have power outputs of less than 100 kW and are termed *microhydropower* systems (**Figure 16.32**).[58] Microhydropower is one of the world's oldest and most common energy sources. Numerous sites in many areas have potential for producing small-scale electrical power; mountainous areas are particularly promising because potential energy from stream water is readily available. Microhydropower development is, by its nature, very site specific, depending on local regulations, the area's economic situation, and hydrologic limitations.

Innovative new ways to develop water power are the subject of ongoing research and development. For example, the energy of ocean waves striking the shore can be used to compress air that is forced through a turbine producing electricity. Another plan is to use the energy of a slow-moving river to produce electricity. The idea is to place vertical obstructions to flow on the river bed that create perturbations of flow that vibrate to produce energy.

Hydropower can be used to generate either electrical power or mechanical power to run machinery. Hydroelectric plants may help cut the high cost of importing energy and help small operations become more independent of local utility providers.[58]

Tidal Power. Another form of water power might be derived from ocean tides in a few places where there is favorable topography, such as the Bay of Fundy region of the northeastern United States and Canada. The tides in the Bay of Fundy have a maximum rise of about 15 m (50 ft). A minimum rise of about 8 m (26 ft) is necessary to even consider developing **tidal power**.

Tidal power is harnessed by building a dam across the entrance to a bay, creating a basin on the landward side of the dam. The dam creates a difference in water level between the ocean and the basin. Then, as the water in the basin rises or falls, it can be used to turn hydraulic turbines that produce electricity. A tidal power station on the River Rance near Saint

FIGURE 16.32 Microhydropower Rush Creek microhydropower station at Silver Lake in the Sierra Nevada of California. *(Edward A. Keller)*

Malo, France, produces more than 200,000 kW of electricity from 24 power units across the dam.

Water Power and Environment. Water power is clean power. It requires no fuel burning, does not pollute the atmosphere, produces no radioactive or other waste, and is efficient. There is an environmental price to pay, however. Water falling over high dams may trap nitrogen gas, which is the major gas in air. The nitrogen then enters the blood of fish, expands, and kills them. This process is analogous to what happens to scuba divers when they rise to the surface too fast and get "the bends." Nitrogen has killed many migrating game fish in the Pacific Northwest. Furthermore, dams trap sediment that would otherwise reach the sea and replenish the sand on beaches. Building dams to harness water's power can also cause the displacement of people, loss of land to the reservoir, loss of wildlife, and adverse changes to the river ecology and hydrology downstream. In addition, many people do not want to turn wild rivers into a series of lakes by building intermittent dams. In fact, in the United States, several dams have been removed, and others are being considered for removal as a result of the adverse environmental impacts their presence is causing.

Despite the inherent problems associated with dams, the world's largest dam has been constructed in China. The Three Gorges Dam (completed in 2006) on the Yangtze River displaced more than a million people from their homes, drowning 13 cities, 1300 villages, farm fields, archeology sites, and highly scenic river gorges (**Figure 16.33**). The dam contributed to the extinction of the Yangtze river dolphin. The habitat for many other plants and animals was fragmented, as mountain tops became islands in the giant reservoir, resulting in loss of species diversity. The dam is about 185 m (607 ft) high and more than 1.6 km (1 mi) wide, and, when filled in October 2010 (it took several years to fill) produced a reservoir nearly 600 km (373 mi) long. There is concern that the reservoir will become polluted by raw sewage and industrial pollutants currently disposed of in the river, turning the long narrow reservoir into an open sewer. It might also degrade or eliminate deep-water shipping harbors at the upstream end of the reservoir, where sediments will most likely be deposited. On a more positive note, 26 giant turbines will produce about 18,000 MW of electricity, the equivalent of 18 large nuclear or coal-burning power plants. However, opponents of the dam point out that a series of dams on tributaries to the Yangtze could have produced electrical power while not causing environmental damage to the main river.[59]

While the future growth of large-scale water power is limited because of objections to dam building and


(a)


(b)

FIGURE 16.33 Three Gorges Dam on China's Yangtze River (a) Qutang Gorge and (b) construction of temporary locks near the dam site on Xiling Gorge. *(Bob Sacha/Bob Sacha Photography)*

the fact that many good sites for dams are already utilized, there seems to be increased interest in microhydropower, or small dams for supplying electricity or mechanical energy. However, the environmental impact of numerous microhydropower installations in an area may be considerable. The sites change the natural stream flow, affecting the stream biota and productivity. Small dams and reservoirs also tend to fill more quickly with sediment than larger installations, so their useful life is shorter.

Because microhydropower development can adversely affect the stream environment, careful consideration must be given to its development over a wide region. A few such sites may cause little environmental degradation, but, if the number becomes excessive, the impact over a wider region may be appreciable. This is a consideration that must be applied to many forms of technology that involve small sites. The impact of a single site on a broad region may be nearly negligible, but as the number of sites increases, the total impact may become significant.

Wind Power

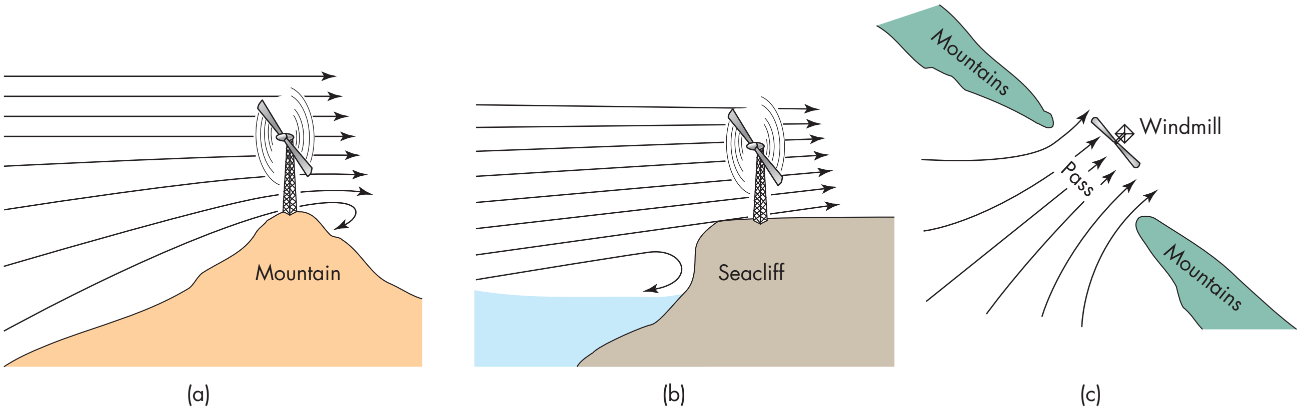
Wind power, like solar power, has evolved over a long period of time, beginning with early Chinese and Persian civilizations. Wind has propelled ships and has driven windmills to grind grain or pump water. More recently, wind has been used to generate electricity. Winds are produced when differential heating of Earth's surface creates air masses with differing heat contents and densities. The potential for energy from the wind is tremendous; however, there are problems with its use because wind tends to be highly variable in time, place, and intensity. Nevertheless, wind power is one of the fastest-growing, most promising, and technologically advanced sources of alternative energy, doubling every few years.[47]

Wind prospecting has become an important endeavor. On a national scale, the areas with the greatest potential for wind energy are the Pacific Northwest coastal area, the coastal region of the northeastern United States, and a belt extending from northern

Texas through the Rocky Mountain States, the Dakotas, Indiana, and Illinois. There are other good sites, however, such as mountainous areas in North Carolina and the northern Coachella Valley in southern California. Chicago is called the "Windy City." Although Chicago is not significantly windier than Los Angeles, Boston, or New York, the region has breezy conditions that favors wind power. For example, in northern Indiana about halfway from Indianapolis to Chicago a successful wind farm is producing enough electricity to power 60,000 homes.

At a particular site, the direction, velocity, and duration of wind may be quite variable, depending on the local topography and on the regional to local magnitude of temperature differences in the atmosphere. Even at good sites, wind generally produces less than 30 percent of what it would if it were available all day, every day. Furthermore, it is often more windy at night, when demand for electricity is low.[47] For example, wind velocity often increases over hilltops, or wind may be funneled through a mountain pass. The increase in wind velocity over a mountain is due to a vertical convergence of the wind, whereas, in a pass, the increase is partly due to a horizontal convergence (**Figure 16.34a–c**). Because the shape of a mountain or a pass is often related to the local or regional geology, prospecting for wind energy is a geologic as well as a geographic and meteorological problem.

Significant improvements in the size of wind turbines and the amount of power they produce were made in recent years, when many European countries and the United States became interested in large-scale wind turbines. In the United States, thousands of wind turbines are located on wind farms (Figure 16.34d). Large state-of-the-art wind turbines are much larger, each producing 3 to 5 MW, enough power for several thousand homes. Advantages of wind power are that wind is a widespread, abundant, inexhaustible resource; wind power has become an inexpensive source of energy (cost-competitive with coal, less expensive than nuclear power, but more



(d)

FIGURE 16.34 Areas with increased wind resources How wind may be converged and velocity increased by topography, vertically (a, b) or horizontally (c). Tall wind turbines are necessary on hilltops or on the top of a sea cliff, to avoid near-surface turbulence. (d) Older wind farm in California. Newer wind turbines are larger. *(Glen Allison/Getty Images)*

expensive than natural gas); and wind power is a clean source of electricity that doesn't cause air pollution or release carbon dioxide that changes climate. For these reasons, wind power is the fastest-growing energy source in the world. However, wind power does have some adverse effects:

- Wind turbines may kill birds, especially large birds of prey, such as hawks and falcons, that fly into the blades while focused on prey. Newer turbines are much safer for birds than older ones.
- Large wind turbines farms require land for roads, wind turbines pads, and other equipment.
- Wind turbines may degrade an area's scenic resources.
- Tall wind turbines may interfere with air traffic.

The growth of wind power in the past decade has been astounding—approximately 30 percent per year, compared with the 1 percent to 2 percent per year growth of oil. Wind power in the United States is doubling about every 2 years. It is believed that in just three states—Texas, South Dakota, and North Dakota—sufficient wind energy resources exist to satisfy the electricity needs of the entire country. Some of the world's largest wind farms are located in Washington and Oregon, on ridges above the Columbia River. The wind farms produce up to 2,700 MW of electricity during peak wind conditions for power generation, equivalent to nearly three large nuclear power plants. On average about 30 percent of peak energy is produced. Most of the power is sent south to California.

China burns tremendous amounts of coal at a tragic environmental cost, including the exposure of millions of people in cities to mixtures of deadly gases and particulates. Similarly, rural China's exposure to the smoke from burning coal in homes has increased the threat of lung cancer by a factor of 9 or more. As China endures these environmental costs, it is investing heavily in wind power[52,60]

Wind power is being taken seriously. Sufficient wind power is generated in the United States to supply electricity to several million suburban homes. Wind now provides about 2 percent of the world's demand for electricity, and its growth rate suggests that it will be a major power supplier in the relatively near future. One scenario suggests that wind power could supply 10 percent of the world's electricity in the next few decades. In the long run, wind power could provide more energy than hydropower.[60]

A potential slowdown in the development of wind energy is the recent drop in the price of natural gas. If gas continues to be abundant and cheap in the next few decades, power plants may burn more gas at the expense of renewable energy sources, such as wind. Nevertheless, in the long run, wind energy will remain a viable source of energy.

The United States in 2009 was the world leader in production of wind energy, at nearly 35,000 MW. This is equivalent to about 35 large fossil fuel or nuclear power plants. China at 26,000 MW is second in the world and Germany is a close third. China is planning massive expansion in wind power and may surpass the United States in the near future.

Biofuels

Biofuel is a new name for the oldest fuel used by humans. Our Pleistocene ancestors burned wood to keep warm and to cook food. Biofuel energy sources are organic matter, such as plant material and animal waste. Biofuel is organic matter that can be burned directly or converted to a more convenient form and then burned. For example, we can burn wood in a stove or convert it to charcoal and then burn it. Biomass has provided a major source of energy for human beings throughout most of the history of civilization. When North American forests were cleared for agriculture, a technique known as *girdling* was used. Girdling involved cutting through the bark all the way around the base of a tree. After girdling had killed the tree, the settlers would then burn the forests to clear the land for farming.

Firewood is the best-known and most widely used biofuel, but there are many types of biomass fuel. In India and other countries, cattle dung is burned for cooking. Peat, a form of compressed dead vegetation, provides heating and cooking fuel in northern countries such as Scotland, where it is abundant.

More than 1 billion people in the world today use wood as their primary source of energy for heat and cooking. Energy from biomass can be generated directly by burning biomass to produce electricity or by the distillation or processing of biomass (i.e., corn, grasses, and algae) to produce biofuels, such as ethanol, methanol, biodiesel, or methane.[47,61]

The primary sources of biofuels in North America are forest products, agricultural products, and combustible urban waste. Manure from livestock or

other organic waste can be digested by microorganisms to form methane and then burned to produce electricity or be used in fuel cells. Using biogenic methane from manure is highly preferable to allowing its release into the atmosphere, where it contributes to global warming.[61]

16.10 Conservation, Efficiency, and Cogeneration

Earlier in this chapter, we established that we must become accustomed to living with uncertainty concerning the availability, cost, and environmental effects of energy use. Furthermore, we can expect that serious social, economic, and political shocks will continue to occur, disrupting the flow of energy to various parts of the world.

Supply and demand for energy are difficult to predict because the technical, economic, political, and social assumptions underlying projections are constantly changing. Large annual variations in energy consumption must also be considered: Energy consumption peaks during the winter, with a secondary peak occurring in the summer. Future changes in population or intensive conservation measures may change this pattern. Better building design and more reliance on solar energy can also contribute to changing the existing energy usage pattern.

There has been a strong movement to change patterns of energy consumption through measures such as conservation, increased efficiency, and cogeneration. **Conservation** of energy refers to a moderation of our energy demand. Pragmatically, this means adjusting our energy uses to minimize the expenditure of energy necessary to accomplish a given task. **Efficiency** entails designing and using equipment that yields more power from a given amount of energy, while wasting less energy.[62] Finally, **cogeneration** refers to a number of processes that capture and use some of the waste heat produced by power generation and industrial operations, rather than simply releasing it into the atmosphere or into water, where it may cause thermal pollution.[63]

The three concepts *conservation*, *increased efficiency*, and *cogeneration* are interrelated. For example, when electricity is produced at large coal-burning power stations, sizable amounts of heat may be emitted into the atmosphere. Typically, three units of fuel burn to produce one unit of electricity, an energy loss of about 67 percent. The use of a "unit of fuel" is arbitrary. It could, for example, be a barrel of oil or a ton of coal. Cogeneration, which involves recycling of that waste heat, can increase the efficiency of a typical power plant from 33 percent to as high as 75 percent. Put another way, cogeneration reduces energy loss from 67 percent to as little as 25 percent.

16.11 Energy Policy for the Future

Energy policy today is at a crossroads. One road leads to the development of technologies, which involves finding ever-greater amounts of fossil fuels and building larger, centralized power plants. Following this road means continuing "business as usual." This is the more comfortable approach; it requires no new thinking or realignment of political, economic, or social conditions. It also involves little anticipation of the inevitable depletion of the fossil fuel resources.

Proponents of the business-as-usual path argue that environmental problems have occurred in some countries because people have had to utilize local resources, such as wood, for energy, rather than, say, for land conservation and erosion control. Business-as-usual supporters believe that the way to solve these problems is to provide people with cheap energy that utilizes more intensive industrialization and technology. Furthermore, the United States and other countries with sizable resources of coal or petroleum should exploit these resources to prevent environmental degradation of their own countries. Proponents of this view maintain that allowing the energy industry the freedom to develop available resources ensures a steady supply of energy and less total environmental damage than if the government regulates the energy industry. They point to the present increase in the burning of firewood across the United States as an early indicator of the effects of strong governmental controls on energy supplies. The eventual depletion of forest resources, they maintain, will have a detrimental effect on the environment, as it has in so many other countries. The business-as-usual path continues to dominate energy planning in the United States, but there are signs that energy policy is changing.

One of the champions for change in energy policy is Amory Lovins, who argues for energy alternatives that are renewable, flexible, decentralized, and environmentally benign.[64] We now appear to be

moving slowly from the business-as-usual approach to energy policy in the United States to strategies that increase energy efficiency, increase alternative energy sources, transition from oil and coal to other energy sources or greatly reduce the environmental consequences of burning coal, and reduce our dependency on foreign oil; the way to do this has not been decided, but perhaps it will involve using more natural gas and nuclear power and other alternative energy sources.

In the United States today, we annually consume approximately 100 EJ of energy. Projections suggest that U.S. energy consumption in the year 2050 will be about 160 EJ. A big question is, what will be the sources for the anticipated growth in energy consumption? Will we follow past policy and business as usual (i.e., coal, oil, and nuclear power), or will we turn to alternative energy sources (e.g., wind, solar, geothermal)? What seems certain is that our energy sources will be more diversified in the future than they are today.[65,66]

Sustainable Energy Policy

Energy planning for the future is complicated; we know that burning fossil fuels is degrading our global environment. We are seeking an new energy path because[65–67] (1) the age of cheap oil is coming to an end, and this is a reality, whether it comes this year or 20 years from now; (2) technology and economic opportunities are favorable for the development and use of much more alternative, renewable energy; and (3) using much less fossil fuel will help reduce environmental degradation by reducing emissions of carbon dioxide and air pollutants and by increasing security. Although there is sufficient coal to last hundreds of years, proponents would prefer to use sustainable energy coal as a short, transitional energy source rather than as a long-term energy source. Others would argue for greatly reducing the use of coal and using natural gas as the transitional energy source to renewable sources. In their view, development of a **sustainable energy policy** means finding useful sources of energy that can be maintained and that do not pollute the atmosphere, cause climatic perturbations, such as global warming, or present unacceptable risk.

The change to new, sustainable energy policy would, presumably, involve continued utilization of fossil fuels in some form for transportation. Electrical power will continue to be essential for many purposes, which means using more alternative energy (including nuclear power) and developing clean ways to use coal. The energy path we take must be capable of supplying the energy we require for human activities without endangering the planet. This is the heart of the concept of sustainable energy policy.

Making The Connection

Linking the Opening Case History About Energy Transition to the Fundamental Concepts

Consider and discuss the following questions:

1. What are the impacts of population increase on a potential transition from oil to other energy sources?
2. For sustainable energy planning, what needs to be done during the transition?
3. How is the transition from oil potentially linked to hazards, such as conflicts between nations and health hazards?
4. How do science and values link to future planning during the transition from oil to other energy sources? In other words, what do our values have to do with future energy choices?

Summary

We are approaching the time of peak oil, when about one-half of the recoverable oil in the world will have been used. As a result, we will need to transition from oil to other energy sources. History tells us this transition could take many decades to perhaps a century. Likely energy sources during the transition are

natural gas, nuclear power, and renewable sources, such as wind and solar energy.

The ever-increasing world population's appetite for energy is staggering. It is time to seriously question the need and desirability of an increasing demand for electrical and other forms of energy in industrialized societies. Quality of life is not necessarily directly related to greater consumption of energy.

The fossil fuels—coal, oil, and natural gas—are essentially stored solar energy in the form of organic material that has escaped destruction by oxidation. Although ongoing geologic processes formed these fuels, they are too slow to be of use to us; fossil fuels are, therefore, considered to be nonrenewable resources. The environmental disruption associated with exploration and development of these resources must be weighed against the benefits gained from the energy. This development is not an either-or proposition; good conservation practices, combined with pollution control and reclamation, can help minimize the environmental disruption associated with fossil fuels.

There are still vast supplies of coal in the world, 25 percent of which are located in the United States. The grade, or carbon content, of coal determines its value as a fuel, while its sulfur content determines how much it pollutes the atmosphere with sulfur oxides.

Oil is found in large deposits called fields; most fields are located near modern and ancient plate boundaries. Oil fields have been extensively mined by oil wells that pump oil and gas to the surface. We are approaching the time known as peak oil when we will have used about half of Earth's total oil. Following the peak, production will decrease and there may be a gap between demand and production. Barring discovery of many major new fields, shortages of oil and gas will occur in the future. The impending shortages have resulted in pressure to develop new oil fields, some in sensitive wilderness areas, such as the Arctic National Wildlife Refuge. Oil can be recovered from Earth materials called oil shales and tar sands, but mining techniques that are economically and environmentally sound have not been fully developed. The potential for environmental disruption exists at every stage of oil development and use; disruptions include oil spills from tankers and air pollution from burning of petroleum products in automobiles and power plants.

Natural gas reserves have dramatically increased in recent years, especially with tight gas. As a result, natural gas is a likely candidate as an energy source useful in the transition from oil to alternative energy sources.

Nuclear fission produces vast amounts of heat that can be used to generate electricity in a nuclear power plant. It also produces radioactive wastes that must be safely disposed of. Fission will remain an important source of energy, but the possibility of environmental and health hazards, as well as the increasing cost of constructing large nuclear power plants, remain as factors to be considered. Finally, we continue to struggle with the problem of radioactive waste disposal—a scientific, economic, social, and political issue involving risk management.

Use of geothermal energy will become more widespread in the western United States, where natural heat flow from Earth is relatively high. Although the electrical energy produced from the internal heat of Earth will probably not exceed 10 percent of the total electrical power generated, it can still be significant. Geothermal energy has an environmental price. Surface subsidence may be caused by the withdrawal of fluids and heat; in addition, earthquakes may be caused by the injection of hot wastewater back into the ground.

Renewable sources of energy depend on solar energy and can take a variety of forms, including direct solar, water, wind, and energy from biomass, including recycled biomass from urban waste. These energy sources are generally used to produce electrical power. They will not be depleted and are, thus, dependable in the long term. They have varying attributes but, generally, cause little environmental disruption, although the burning of biomass does pollute the atmosphere. However, most of these sources are local and intermittent, and some are still expensive to produce. Continued growth and development of solar energy and wind power, as well as development of new technology and innovations such as fuel cells, will become more important in the future. Solar and wind power, because they are abundant, inexhaustible, and clean, are the world's fastest-growing sources of energy. Hydropower will undoubtedly continue to be an important source of electricity in the future, but it is not expected to grow much in the United States because of lack of potential sites and environmental considerations.

Energy for the future will continue to be uncertain. It does seem certain, however, that we will continue to look more seriously at conservation, energy efficiency, and cogeneration. The most likely targets for energy efficiency, conservation, and cogeneration are in the area of space heating for homes and for various manufacturing processes and automobiles. These areas collectively account for approximately 60 percent of the total energy used in the United States today.

We are at a crossroads concerning energy policy. The choice is between centralized, high-technology energy sources, using fossil fuels, and flexible, renewable energy sources. Perhaps the best path will be a mixture of the old and the new, ensuring a rational, smooth shift from our dependence on fossil fuels. Our goal is to develop a sustainable energy plan that supplies the energy we need but does not harm the environment or endanger our national security.

Key Terms

acid rain (p. 559)
alternative energy (p. 575)
biofuel (p. 581)
coal (p. 542)
coal-bed methane (p. 552)
cogeneration (p. 582)
conservation (p. 582)
efficiency (p. 582)
fossil fuel (p. 539)
fuel cell (p. 577)
geothermal energy (p. 571)
natural gas (p. 549)
nuclear energy (p. 561)
oil (p. 549)
peak oil (p. 538)
solar energy (p. 575)
sustainable energy policy (p. 583)
tidal power (p. 577)
tight gas (p. 553)
water power (p. 577)
wind power (p. 579)

Review Questions

1. What is peak oil, and why is it important?
2. What determines the type of a coal, and why is type important?
3. What is tight gas, and why is it important?
4. What are the major environmental impacts of exploration for and development of oil and gas?
5. Define *nuclear fission*.
6. What are the major environmental concerns associated with nuclear energy?
7. What is geothermal energy?
8. How can groundwater at normal temperatures be used as an energy source?
9. What are the major renewable energy sources?
10. Are there any environmental concerns associated with hydroelectric power? If so, what are they?
11. What are the sources and potential environmental impacts associated with the transition from oil to other energy sources?
12. What is cogeneration?
13. What do we mean by sustainable energy policy?

Critical Thinking Questions

1. When we first started using fossil fuels, particularly oil, we did not know, nor were we particularly concerned about, potential environmental impacts of developing and burning oil. Suppose, at that time, we had completed an environmental impact report concerning the use of oil and had been able to predict consequences, such as air pollution, toxicity, and acid rain. Do you think we would have developed the use of oil as fast as we did and become so dependent on it? Justify your answer.
2. Do you think that peak oil will be a defining moment in human history? Why or why not?
3. Sustainable energy development means developing an energy policy and energy sources that will provide the energy society needs without harming the environment. Do you think this is possible? Outline a plan of action to move the United States toward sustainable energy development.
4. How long do you think it will take to transition from oil (mostly used in the transportation sector [e.g., cars, buses, trains, planes]) to other sources of energy? Is it possible in 20 years? 50? Why or why not?

Companion Website

www.mygeoscienceplace.com

PEARSON mygeoscience place™ *Introduction to Environmental Geology, 5e* premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Times Beach, Missouri In the 1980s this town became a ghost town: evacuated, abandoned, fenced off, and bulldozed, following discovery of dioxin contamination.
(Tom McHugh/Photo Researchers, Inc.)

17 Soils and Environment

Learning Objectives

Soils are an important part of our environment. Virtually all aspects of the terrestrial environment interact with soils at some level. For example, we depend upon fertile soil to grow our food, and soil properties determine, in part, the suitability of land for uses such as construction and waste disposal. As a result, the protection of soil resources is an important objective. With this in mind, we will focus on the following learning objectives for this chapter:

- **Understand soil terminology and the processes responsible for the development of soils**
- **Understand soil fertility and the interactions of water in soil processes**
- **Be familiar with soil classification**
- **Understand the primary engineering properties of soils**
- **Understand relationships between land use and soils**
- **Know what sediment pollution is and how it can be minimized**
- **Understand how soils affect land use planning**
- **Understand how we can sustain soil resources**

Case History

Times Beach, Missouri

In 1982, Times Beach, Missouri, population 2,400, was a river town located on the banks of the Meramec River just west of St. Louis. The town was founded in 1925 as a resort community to nearby St. Louis. Due to the flood hazard, some of the early homes were built on stilts above normal flood level. The river town eventually became a permanent community. The town in the 1970s was a poor one, and it couldn't afford to pave the streets. In 1983, the town was evacuated and purchased for $36 million by the government; Times Beach became a ghost town when it was discovered that waste oil sprayed on the town's road to control dust contained dioxin (**Figure 17.1**). Dioxin is a colorless crystal composed of oxygen, hydrogen, carbon, and chlorine. It is known to be extremely toxic to mammals and is suspected of being a carcinogen in humans. Horses at stables in the Times Beach area began to die.[1]

There are approximately 75 types of dioxin, which is produced as a by-product during the production of organic chemicals, such as herbicides.[2] Dioxin became a household word during and after the Vietnam War; it is a component of Agent Orange, the name given to herbicides that were used to defoliate large areas in the war zones. Military personnel as well as civilians were exposed to Agent Orange and the dioxin within it. Lawsuit settlements pertaining to dioxin's role in causing diseases in people exposed to it compensated 250,000 Vietnam veterans and their families.

Soil tests at Times Beach determined that the entire area had been contaminated with dioxin that had seeped into the soil from the oil applied to the roads. The decision was made in 1985 to evacuate the town and bulldoze the buildings. Following cleanup (many thousands of tons of contaminated soil were removed and incinerated) and planting of trees, the area today is a state park and bird refuge. The park, called Route 66 State Park, is one of Missouri's newest parks. The park has several kilometers of trails for hiking, biking, and horseback riding. The park has picnic areas and a boat-launching facility that provides access to the Meramec River.[1]

The effects of human exposure to dioxin is a controversial subject. Apparently, there is a cancer risk to

17.1 Introduction to Soils

The big question with soil is: Can the agricultural systems that we depend on to feed a growing human population maintain and improve soil fertility while minimizing soil erosion?[4] **Figure 17.2** (page 590) shows serious soil erosion with the development of shallow gullies in a wheat field in eastern Washington. It appears that many of our agriculture practices are mining the soil. That is, soils are being eroded faster than they are being produced by soil-forming processes. Eventually, agricultural soil loss could erode the foundation of our civilization. Soil erosion has multiple effects, including loss of soil resources and degradation of the quality of the water due to sedimentation. Soil erosion is a problem in urban environments, where vegetation may be removed prior to development. Although we have many safeguards in effect to minimize soil erosion resulting from urbanization, the problem persists in many parts of the United States and is severe in many parts of the world where protection of soil resources may not be a high priority.[4,5] We begin our discussion of soils by defining *soil* and introducing soil types, classification, and processes.

Soil may be defined in several ways. Soil scientists define *soil* as solid Earth material that has been altered by physical, chemical, and biological processes such that it can support rooted plant life. Engineers define *soil* as solid Earth material that can be removed without blasting. Both of these definitions are important in environmental geology. Geologists must be aware of the different definitions; they must also be aware of the research concerning both soil-producing processes and the role of soils in environmental problems. Engineers have developed the field of soil mechanics to quantify engineering properties of soils, such as soil strength and moisture content.

(a)

(b)

FIGURE 17.1 Dioxin pollutes soil in Missouri (a) Times Beach, Missouri, showing a deserted building after dioxin was found to be contaminating the area. *(Art Phillips/Corbis)* (b) Examination of soils contaminated by dioxin at Times Beach, Missouri. The town was evacuated because of the dioxin scare. *(O. Franken/Corbis)*

workers who handle chemicals that contain dioxin, but it is not thought to be a widespread and significant cancer threat to people who are exposed to very low levels of the chemical.[3] Some scientists, including the person who ordered the evacuation, have since stated that the evacuation at Times Beach may have been an overreaction by the government to the perceived hazard of dioxin. Research concerning the potential hazard presented from exposure to dioxin continues, and the controversy concerning its potential harmful effects to people and ecosystems is still being debated.

This chapter will discuss several important aspects of soil formation and problems related to soil erosion and pollution. Soils are of particular importance to environmental geology because the Earth materials we often encounter are soils that we build our homes on and grow our food in. We shall see that, as soil properties vary from place to place, we must adjust our land use if we are to sustain our landscape.

The study of soil properties, particularly with reference to land-use limitations, is becoming an important aspect of environmental work in the following ways:

- In land use planning, the suitability of land for a particular use, or *land capability*, is often determined, in part, by the soils present. Soil properties are especially important for uses such as urbanization, timber management, and agriculture.
- Soils are critical when we consider waste-disposal problems. Interactions between waste, water, soil, and rock often determine the suitability of a particular site for receiving waste.
- The study of soils helps land use planners evaluate natural hazards, including floods, landslides, and earthquakes. Floodplain soils differ from upland soils, and consideration of soil properties helps delineate natural floodplains. Evaluating the relative ages of soils on landslide deposits may provide an estimate of the frequency of slides; this information assists in planning to minimize their impact. Soil studies have also been a tool in establishing the age of Earth materials deformed by faulting; this information leads to better estimation of earthquake recurrence intervals.
- Soils often carry a climatic signal, something that indicates what the past climate was like. For example, calcium carbonate accumulates in desert soils, and organic matter, such as bits of plants, accumulates in some tropical soils. These constituents of soils assist in understanding regional and global climate change. Soil studies also provide important data used to understand how biological and geologic processes were linked in the development of both soils and ecosystems during the past few million years.[6]

FIGURE 17.2 Soil erosion Wheat field in eastern Washington with a serious erosion problem. *(Jack Dykinga/USDA Forest Service)*

17.2 Soil Profiles

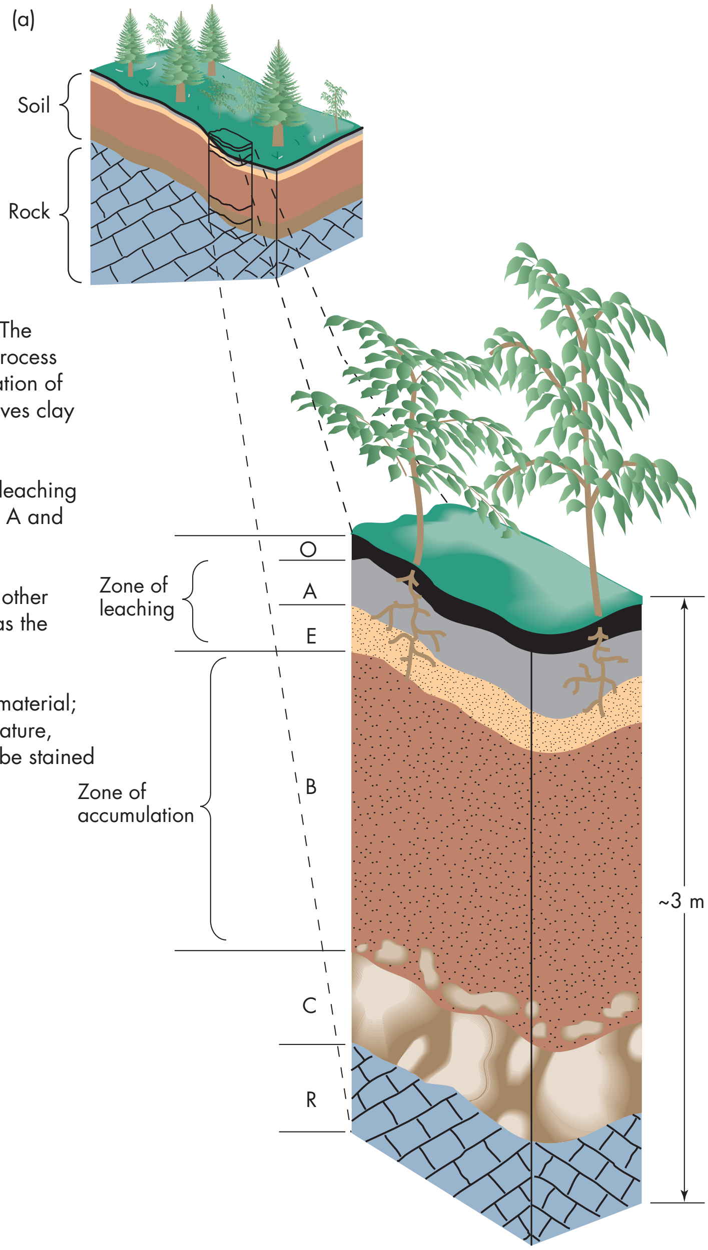
Soil development is a complex process. The rock and hydrologic cycles interact to produce weathered rock materials that are basic ingredients of soils. *Weathering* is the physical and chemical breakdown of minerals and rocks and the first step in soil development (see Chapter 3). Weathered rock is further modified into soil by the activity of soil organisms. This process forms residual or transported soil. Weathered material that remains essentially in place is modified to form a *residual soil* on bedrock. The red soils of the Piedmont in the southeastern United States, formed on igneous and metamorphic rocks, are an example of residual soil. Eroded rock particles that are transported by water, wind, or glaciers and then modified in their new deposition location form *transported soil*. The fertile soils formed on glacial deposits in the midwestern United States are transported soils.

A soil can be considered an open system that interacts with other components of the geologic cycle. The characteristics of a particular soil are a function of climate, topography, parent material (i.e., the rock from which the soil is formed), maturity (i.e., age of the soil), and biological processes.

Soil Horizons

Vertical and horizontal movements of the materials in a soil system create a distinct layering, parallel to the surface, collectively called a **soil profile**. The layers are called zones, or **soil horizons**. Our discussion of soil profiles mentions only the horizons most commonly found in soils. Additional information is available from detailed soils texts.[7–9]

Figure 17.3a shows the common master, or prominent, soil horizons. The *O horizon* and *A horizon* contain highly concentrated organic material, such as decomposing plants. The differences between these two layers reflect the amount of organic material present in each. In general, the O horizon consists almost entirely of plant litter and other organic material, whereas the underlying A horizon contains a good deal of both organic and mineral material. Below the O or A horizons, some soils have an *E horizon*, or zone of leaching, a light-colored layer that is



O. Horizon is composed mostly of organic materials including decomposed or decomposing leaves, twigs, etc. The color of the horizon is often dark brown or black.

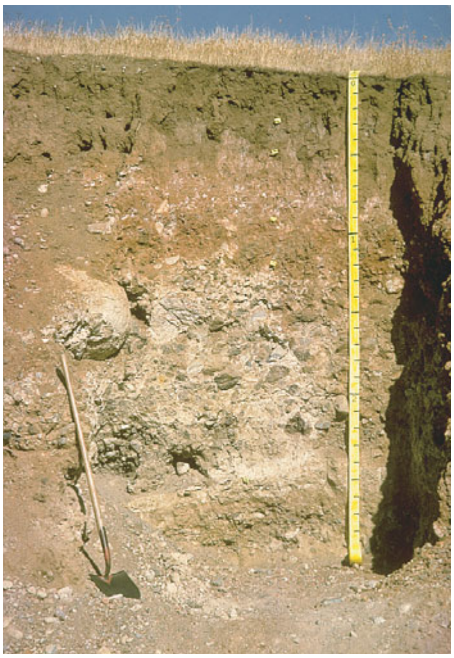
A. Horizon is composed of both mineral and organic materials. The color is often light black to brown. Leaching, defined as the process of dissolving, washing, or draining Earth materials by percolation of groundwater or other liquids, occurs in the A horizon and moves clay and other material such as iron and calcium to the B horizon.

E. Horizon is composed of light-colored materials resulting from leaching of clay, calcium, magnesium, and iron to lower horizons. The A and E horizons together constitute the zone of leaching.

B. Horizon is enriched in clay, iron oxides, silica, carbonate, or other material leached from overlying horizons. Horizon is known as the zone of accumulation.

C. Horizon is composed of partially altered (weathered) parent material; rock is shown here but the material could also be alluvial in nature, such as river gravels in other environments. The horizon may be stained red with iron oxides.

R. Unweathered (unaltered) parent material.



(b)

FIGURE 17.3 Soil profiles (a) Idealized diagram showing a soil profile with soil horizons. (b) Soil profile showing a black A horizon, a light-red B horizon, a white K horizon rich in calcium carbonate, and a lighter C horizon. *(Edward A. Keller)*

leached of iron-bearing components. This horizon is light in color because it contains less organic material than the O and A horizons and little inorganic coloring material, such as iron oxides.

The *B horizon*, or zone of accumulation, underlies the O, A, or E horizons and consists of a variety of materials translocated downward from overlying horizons. Several types of B horizons have been recognized. Probably the most important type of B horizon is the *argillic B horizon* (B_t). An argillic B horizon is enriched in clay minerals that have been translocated downward by soil-forming processes. Environmental geologists are also interested in the *B_k horizon*, which is characterized by accumulation of calcium carbonate. The carbonate coats individual soil particles and may fill some pore spaces within the soil. It does not, however, dominate the structure of the horizon. If a soil horizon is impregnated with calcium carbonate to the extent that its morphology is dominated by the carbonate, it is designated a *K horizon* (Figure 17.3b). Carbonate completely fills the pore spaces in K horizons, often forming layers parallel to the surface. The term *caliche* is often used for an irregular accumulation or layers of calcium carbonate in Earth material near the surface.

The *C horizon* consists of parent material partially altered by weathering processes. It lies directly over the *R horizon*, which is unaltered parent material composed of consolidated bedrock that underlies the soil. Some of the fractures and other pore spaces in the bedrock may contain clay that has been translocated downward.[7]

The term *hardpan* is often used to refer to a hard compacted soil horizon, usually part of the B horizon. Hardpan is often composed of compacted clay or cemented with calcium carbonate, iron oxide, or silica. Hardpan horizons may be nearly impermeable and, thus, restrict the downward movement of soil water.

17.3 Soil Properties

Color

One of the first things we notice about a soil is its color, or the colors of its horizons. The O and A horizons tend to be dark because of their abundant organic material. The E horizon, if present, may be almost white because of the leaching of iron and aluminum oxides. The B horizon shows the most dramatic differences in color, varying from yellow-brown to light red-brown to dark red, depending on the presence of clay minerals and iron oxides. B_k horizons may be light colored because of their carbonates, but they are sometimes reddish as a result of iron oxide accumulation. If a true K horizon has developed, it may be almost white because of the abundance of calcium carbonate. Although soil color can be an important diagnostic tool for analyzing a soil profile, one must be cautious about calling a red layer a B horizon. The original parent material, if rich in iron, may produce a very red soil, even when there has been relatively little soil profile development.

Soil color may be an important indicator of how well a soil drains. Well-drained soils are well aerated, creating oxidizing conditions; for example, in a well-aerated soil, iron produces soil with a red color. Poorly drained soils are wet, and these soils tend to have a yellow color. This distinction is important because poorly drained soils are associated with environmental problems, such as lower slope stability and an inability to be utilized as a disposal medium for household sewage systems.

Texture

The *texture* of a soil depends upon the relative proportions of sand-, silt-, and clay-sized particles (**Figure 17.4**). Clay particles have a diameter of less than 0.004 mm (0.0002 in.); silt particles have diameters ranging from 0.004 to 0.063 mm (0.0002 to 0.003 in.); and sand particles are 0.063 to 2.0 mm (0.003 to 0.08 in.) in diameter. Earth materials with particles larger than 2.0 mm (0.08 in.) in diameter are called gravel, cobbles, or boulders, depending on the particle size.

In the field, soil texture is commonly identified by estimation and then refined in a laboratory by separating and determining the proportions of the sand, silt, and clay. A useful field technique for estimating the size of sand-sized or smaller soil particles is as follows: It is sand if you can see individual grains, silt if you can see the grains with a 10× hand lens, and clay if you cannot see grains with such a hand lens. Another method is to feel the soil. Sand is gritty; it crunches between the teeth. Silt feels like baking flour, and clay is cohesive. When mixed with water, smeared on the back of the hand, and allowed to dry, clay cannot easily be dusted off, whereas silt or sand can.

Structure

Soil particles often cling together in aggregates called *peds* that are classified according to shape into several types. **Figure 17.5** shows some of the common

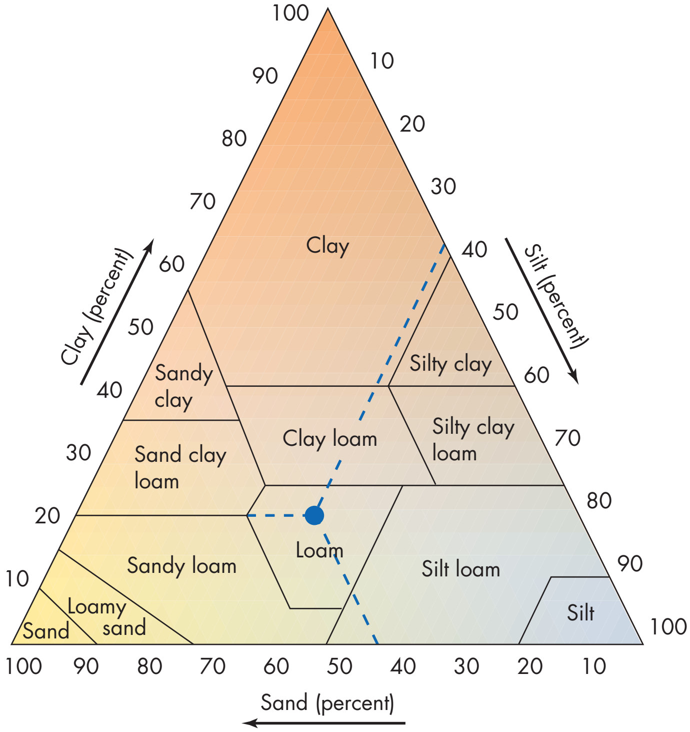
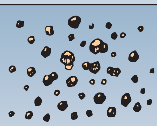
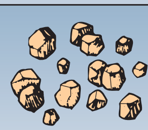
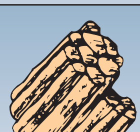
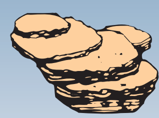


FIGURE 17.4 Soil texture classes The classes are defined according to the percentage of clay-, silt-, and sand-sized particles in the soil sample. The area defined by the point connected by dashed lines represents a soil composed of 40 percent sand, 40 percent silt, and 20 percent clay, which is classified as loam. Loam is a soil composed of sand, silt, and clay sized particles in relatively even (20–40%) concentration. Variable organic material is also present. Loam soils are good for agriculture because they retain nutrients, and water, while allowing water to flow through. *(From U.S. Department of Agriculture)*

FIGURE 17.5 Soil structure Types and description of soil structure (peds).

Types of peds	Typical size range	Horizon usually found in	Comments
Granular 	1–10 mm	*A*	Can also be found in *B* and *C* horizons
Blocky 	5–50 mm	B_t	Are usually designated as angular or subangular
Prismatic 	10–100 mm	B_t	If columns have rounded tops, structure is called columnar
Platy 	1–10 mm	*E*	May also occur in some *B* horizons

structures of peds found in soils. The type of structure present is related to soil-forming processes, but some of these processes are poorly understood.[7] For example, granular structure is fairly common in A horizons, whereas blocky and prismatic structures are most likely to be found in B horizons. Soil structure is an important diagnostic tool for evaluating the development and approximate age of soil profiles. In general, as the profile develops with time, structure becomes more complex and may go from granular to blocky to prismatic as the clay content in the argillic B horizons increases.

Relative Soil Profile Development

Most environmental geologists will not have occasion to make detailed soil descriptions and analyses of soil data. However, it is important for geologists

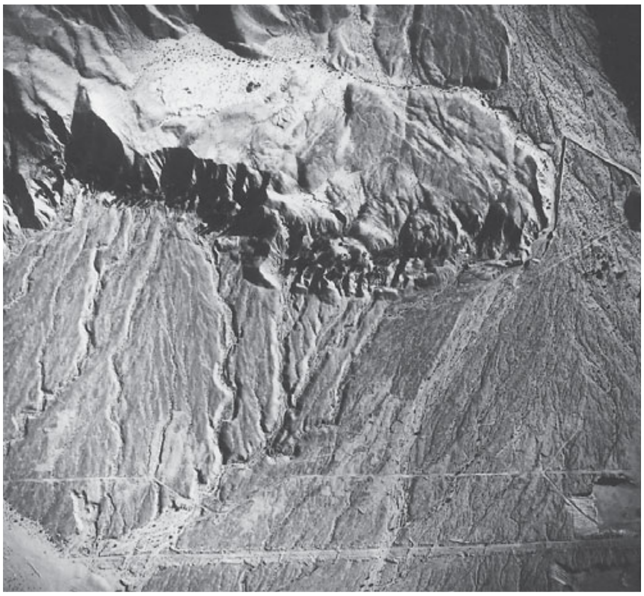
to recognize differences among weakly developed, moderately developed, and well-developed soils—that is, to recognize their **relative profile development**. These distinctions are useful in the preliminary evaluation of soil properties and help determine whether the opinion of a soil scientist is necessary in a particular project:

- *A weakly developed soil profile* is generally characterized by an A horizon directly over a C horizon (with no B horizon or one that is very weakly developed). The C horizon may be oxidized. Such soils tend to be only a few hundred years old in most areas, but they may be several thousand years old in others.
- *A moderately developed soil profile* may consist of an A horizon overlying an argillic B_t horizon that overlies the C horizon. A carbonate B_k horizon may also be present but is not necessary for a soil to be considered moderately developed. These soils have a B horizon with translocated changes, a better-developed texture, and redder colors than those that are weakly developed. Moderately developed soils often date from at least the Pleistocene (i.e., are more than 10,000 years old).
- *A well-developed soil profile* is characterized by redder colors in the B_t horizon, more translocation of clay to the B_t horizon, and stronger structure. A K horizon may also be present but is not necessary for a soil to be considered strongly developed. Well-developed soils vary widely in age, with typical ranges between 40,000 and several hundred thousand years and older.

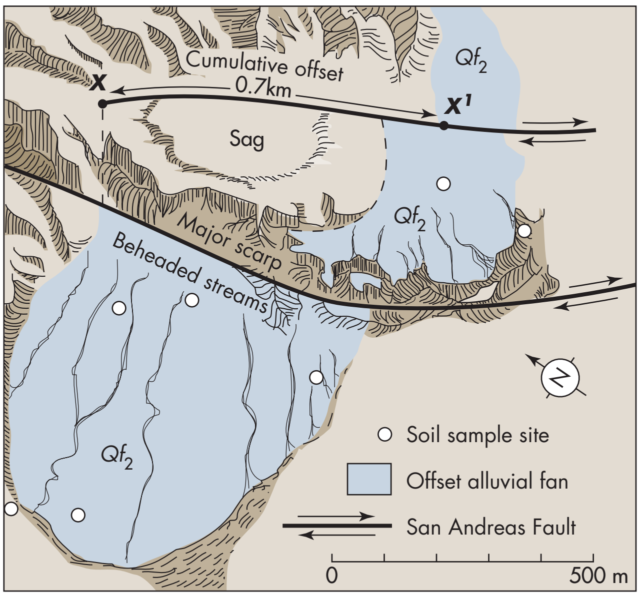
Soil Chronosequences

A **soil chronosequence** is a series of soils arranged from youngest to oldest on the basis of their relative profile development. Such a sequence is valuable in hazards work because it provides information about the recent history of a landscape, allowing us to evaluate site stability when locating critical facilities such as a waste disposal operation or a large power plant. A chronosequence combined with numerical dating (i.e., applying a variety of dating techniques, such as radiocarbon ^{14}C, to obtain a date in years before the present time of the soil) may provide the data necessary to make such inferential statements as, "There is no evidence of ground rupture due to earthquakes in the past 1,000 years" or "The last mudflow was at least 30,000 years ago." It takes a lot of work to establish a chronosequence in soils in a particular area. However, once such a chronosequence is developed and dated, it may be applied to a specific problem.

Consider, for example, the landscape shown in **Figure 17.6**, an offset alluvial fan along the San Andreas fault in the Indio Hills of southern California. The fan is offset about 0.7 km (70,000 cm). Soil pits excavated in the alluvial fan suggest that it is at least



(a)



(b)

FIGURE 17.6 Offset alluvial fan along the San Andreas fault near Indio, California (a) Aerial photograph. *(USGS)* (b) Sketch map.

20,000 years old but younger than 45,000 years. The age was estimated on the basis of correlation with a soil chronosequence in the nearby Mojave Desert, where numerical dates for similar soils are available. Soil development on the offset alluvial fan allowed the age of the fan to be estimated. This allowed the slip rate (i.e., the amount of offset of the fan divided by the age of the fan—that is, 70,000 cm ÷ 20,000 years) for this part of the San Andreas fault to be estimated at about 3.5 cm/yr (35 m/1,000 yr).[10,11] More recent work, using a numerical dating technique known as *exposure dating*, suggests the age 35,500 ± 2,500 years. This new and more accurate estimation of age provides a maximum slip rate of about 2 cm per year. Thus, the earlier soil date has been improved by more recent technology. As numerical dating has improved, the use of soil development as a dating tool has decreased.

The slip rate for this segment of the fault was not previously known. The rate is significant because it is a necessary ingredient in the eventual estimation of the probability and the recurrence interval of large, damaging earthquakes.

17.4 Soil Fertility

A soil may be considered a complex ecosystem. A single cubic meter of soil may contain millions of living things, including small rodents, insects, worms, algae, fungi, and bacteria. These organisms are important for mixing and aerating the soil particles. They also help release or convert nutrients in soils into forms that are useful for plants.[12] **Soil fertility** refers to the capacity of soil to supply nutrients, such as nitrogen, phosphorus, and potassium, needed for plant growth when other factors are favorable.[13]

Soils that developed on some floodplains and glacial deposits contain sufficient nutrients and organic material to be naturally fertile. Other soils, developed on highly leached bedrock or on loose deposits with little organic material, may be nutrient poor and have low fertility. Soils are often manipulated to increase plant yield by applying either fertilizers to supply nutrients or materials that improve the soil's texture and moisture retention. Soil fertility can be reduced by soil erosion or leaching that removes nutrients, by interruption of natural processes that supply nutrients, such as flooding, or by continued use of pesticides that alter or damage soil organisms.

The development and maintenance of many terrestrial ecosystems depend upon soil as a basic component of the system. Interactions between physical and biochemical processes operate over variable scales of time (hundreds to thousands of years) and space (from less than 1 km^2 to thousands of square kilometers) to produce soils that help support complex ecosystems. Soils go through stages of development, sustaining, and degrading.[6] Development is a relatively fast process that starts with a new substrate, or layer, such as sediment from a volcanic eruption or flood. Chemical weathering of minerals releases chemicals that can be used by a variety of organisms, including plants, that build soils. Sustaining soils involves longer time lines—thousands to several millions of years, during which additional minerals in the soils continue to weather, forming clays. Soil degradation occurs as minerals necessary to support an ecosystem are depleted by a variety of near-surface physical, hydrologic, and biological processes. A physical process, soil erosion, can remove upper soil horizons and their nutrients. In some cases, soil degradation processes may be reduced. For example, nutrients contained in dust from the deserts of Africa may reach islands of the Pacific, helping maintain soil fertility after weathering and water moving through the soil have removed some of the original mineral nutrients in soils.[6]

17.5 Water in Soil

If you analyze a block of soil, you will find that it is composed of bits of solid mineral and organic matter with pore spaces between them (**Figure 17.7**).

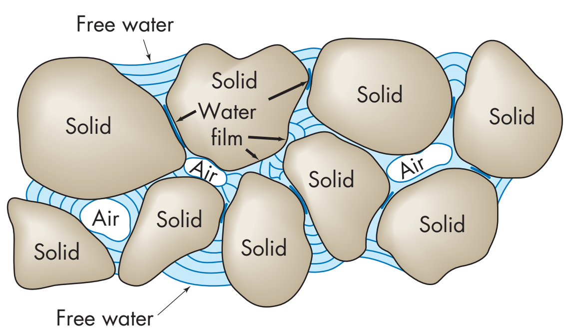


FIGURE 17.7 Water in soils Partly saturated soil, showing particle–water–air relationships. Particle size is greatly magnified. The attraction between the water and the soil particles, or the surface tension, develops a stress that holds the grains together. This apparent cohesion is destroyed if the soil dries out or becomes completely saturated. *(After Pestrong, R. 1974.* Slope Stability. *New York: American Geological Institute and McGraw-Hill)*

The pore spaces are filled with gases (mostly air) or liquids (mostly water). If all the pore spaces in a block of soil are completely filled with water, the soil is said to be in a *saturated* condition; otherwise, it is said to be *unsaturated*. Soils in swampy areas may be saturated year-round, whereas soils in arid regions may be only occasionally saturated.[14]

The amount and movement of water through soils are important research topics. Both are linked to water pollution problems, such as the movement of gasoline from leaking underground tanks or the migration of liquid pollutants from waste-disposal sites.

17.6 Soil Classification

Terminology and classification of soils pose unique problems in environmental geology. We are often interested in both soil processes and human use of soil. A classification system, or *taxonomy*, that includes engineering as well as physical and chemical properties would be most appropriate, but none exists. We must, therefore, be familiar with two separate systems of soil classification: soil taxonomy, used by soil scientists, and the engineering classification, which groups soils by material types and engineering properties.

Soil Taxonomy

Soil scientists have developed a comprehensive and systematic classification of soils known as *soil taxonomy*, which emphasizes the physical and chemical properties of the soil profile. This classification is a sixfold hierarchy, with soils grouped into orders, suborders, great groups, subgroups, families, and series. The eleven orders (**Table 17.1**) are mostly

TABLE 17.1 General Properties of Soil Order Used with Soil Taxonomy by Soil Scientists

Order	General Properties
Entisols	No horizon development; many are recent alluvium; synthetic soils are included; often young soils.
Vertisols	Include swelling clays (greater than 35%) that expand and contract with changing moisture content. Generally form in regions with pronounced wet and dry seasons.
Inceptisols	One or more horizons have developed quickly; horizons are often difficult to differentiate; most often found in young but not recent land surfaces; have appreciable accumulation of organic material; most common in humid climates but range from the arctic to the tropics; native vegetation is most often forest.
Aridisols	Desert soils; soils of dry places; low organic accumulation; have subsoil horizon where gypsum, caliche (calcium carbonate), salt, or other materials may accumulate.
Mollisols	Soils characterized by black, organic-rich A horizon (prairie soils); surface horizons are also rich in bases. Commonly found in semiarid and subhumid regions.
Andisols	Soils derived primarily from volcanic materials; relatively rich in chemically active minerals that rapidly take up important biologic elements, such as carbon and phosphorus.
Spodosols	Soils characterized by ash-colored sands over subsoil, accumulations of amorphous iron-aluminum sesquioxides, and humus. They are acid soils that commonly form in sandy parent materials. Are found principally under forests in humid regions.
Alfisols	Soils characterized by a brown or gray-brown surface horizon and an argillic (clay-rich) subsoil accumulation with an intermediate to high base saturation (greater than 35%, as measured by the sum of cations, such as calcium, sodium, magnesium, etc.). Commonly form under forests in humid regions of the midlatitudes.
Ulfisols	Soils characterized by an argillic horizon with low base saturation (less than 35%, as measured by the sum of cations); often have a red-yellow or reddish-brown color; restricted to humid climates and generally form on older landforms or younger, highly weathered parent materials.
Oxisols	Relatively featureless, often deep soils, leached of bases, hydrated, containing oxides of iron and aluminum (laterite), as well as kaolinite clay. Primarily restricted to tropical and subtropical regions.
Histosols	Organic soils (peat, muck, bog).

After Soil Survey Staff. 1994. *Keys to Soil Taxonomy,* 6th ed. Soil Conservation Service, U.S. Department of Agriculture.

based on gross soil morphology (i.e., number and types of horizons present), nutrient status, organic content (plant debris, etc.), color (red, yellow, brown, white, etc.), and general climatic considerations (amount of precipitation, average temperature, etc.). With each step down the hierarchy, more information about a specific soil becomes known.

Soil taxonomy is especially useful for agricultural and related land-use purposes. It has been criticized for being too complex and for lacking sufficient textural and engineering information to be of optimal use in site evaluation for engineering purposes. Nevertheless, a serious Earth scientist must have knowledge of this classification because it is commonly used by soil scientists and Quaternary geologists—those who study Earth materials and the processes of recent (i.e., the past 2.6 million years) Earth history.

Engineering Classification of Soils

The *unified soil classification system*, widely used in engineering practice, is shown in **Table 17.2**. Because all natural soils are mixtures of coarse particles (including gravel and sand), fine particles (including silt and clay), and organic material, the major divisions of this system are coarse-grained soils, fine-grained soils, and organic soils. Each group is based on the predominant particle size or the abundance of organic material in the soil. Organic soils have a high organic content and are identified by their black or gray color and sometimes by an odor of hydrogen sulfide, which smells like rotten eggs. Linkages between the unified soil classification and engineering properties are listed in **Table 17.3**.

TABLE 17.2 Unified Soil Classification System Used by Engineers

		Major Division		Group Symbol	Soil Group Name
COARSE-GRAINED SOILS (more than half of material larger than 0.074 mm)	GRAVELS	Clean gravels	Less than 5% fines	GW	Well-graded gravel
				GP	Poorly graded gravel
		Dirty gravels	More than 12% fines	GM	Silty gravel
				GC	Clayey gravel
	SANDS	Clean sands	Less than 5% fines	SW	Well-graded sand
				SP	Poorly graded sand
		Dirty sands	More than 12% fines	SM	Silty sand
				SC	Clayey sand
FINE-GRAINED SOILS (more than half of material smaller than 0.074 mm)	SILTS, NONPLASTIC			ML	Silt
				MH	Micaceous silt
				OL	Organic silt
	CLAYS, PLASTIC			CL	Silty clay
				CH	High plastic clay
				OH	Organic clay
Predominantly organics				PT	Peat and muck

Note: The value 0.074 mm is the boundary between sand and silt that engineers use. Geologists use 0.063 mm for the same boundary.

TABLE 17.3 Generalized Sizes, Descriptions, and Properties of Soils

Soil	Soil Component	Symbol	Grain Size Range and Description	Significant Properties
Coarse-grained components	Boulder	None	Rounded to angular, bulky, hard, rock particle; average diameter more than 25.6 cm.	Boulders and cobbles are very stable components used for fills, ballast, and riprap. Because of size and weight, their occurrence in natural deposits tends to improve the stability of foundations. Angularity of particles increases stability.
	Cobble	None	Rounded to angular, bulky, hard, rock particle; average diameter 6.5–25.6 cm.	
	Gravel	G	Rounded to angular, bulky, hard, rock particles greater than 2 mm in diameter.	Gravel and sand have essentially the same engineering properties, differing mainly in degree. They are easy to compact, little affected by moisture, and not subject to frost action. Gravels are generally more pervious and more stable and resistant to erosion and piping than are sands. The well-graded* sands and gravels are generally less pervious and more stable than those that are poorly graded and of uniform gradation.
	Sand	S	Rounded to angular, bulky, hard, rock particles 0.074–2 mm in diameter.	
Fine-Grained Components	Silt	M	Particles 0.004–0.074 mm in diameter; slightly plastic or nonplastic regardless of moisture; exhibits little or no strength when air dried.	Silt is inherently unstable, particularly with increased moisture, and has a tendency to become quick when saturated. It is relatively impervious, difficult to compact, highly susceptible to frost heave, easily erodible, and subject to piping and boiling. Bulky grains reduce compressibility, whereas flaky grains (such as mica) increase compressibility, producing an elastic silt.
	Clay	C	Particles smaller than 0.004 mm in diameter; exhibits plastic properties within a certain range of moisture; exhibits considerable strength when air dried.	The distinguishing characteristic of clay is cohesion or cohesive strength, which increases with decreasing moisture. The permeability of clay is very low; it is difficult to compact when wet and impossible to drain by ordinary means; when compacted, is resistant to erosion and piping; not susceptible to frost heave; and subject to expansion and shrinkage with changes in moisture. The properties are influenced not only by the size and shape (flat or platelike) but also by their mineral composition. In general, the montmorillonite clay mineral has the greatest and kaolinite the least adverse effect on the properties.
	Organic matter	O	Organic matter in various sizes and stages of decomposition.	Organic matter present even in moderate amounts increases the compressibility and reduces the stability of the fine-grained components. It may decay, causing voids, or change the properties of a soil by chemical alteration; hence, organic soils are not desirable for engineering purposes.

*The term *well-graded* indicates an even distribution of sizes and is equivalent to *poorly sorted*.

Note: The unified soil classification system does not recognize cobbles and boulders with symbols. The size range for these, as well as the upper limit for clay, are classified according to Wentworth (1922).

After Wagner, *The Use of the Unified Soil Classification System by the Bureau of Reclamation*. International Conference on Soil Mechanics and Foundation Engineering, Proceedings, London, 1957.

17.7 Engineering Properties of Soils

The water table acts as a transition zone within Earth. Pores in rocks below the water table are saturated; those above are not. Soil above the water table has three distinct parts, or phases: solid material, liquid, and gas, such as air or carbon dioxide. A soil's usefulness is greatly affected by the variations in the proportions and structure of the three phases. The types of solid materials, the particle size, and the water content are probably the most significant variables that determine engineering properties of soils. Important engineering properties are strength, sensitivity, compressibility, erodibility, hydraulic conductivity, corrosion potential, ease of excavation, and shrink–swell potential. Table 17.3 lists the linkages between the unified soil classification system and engineering properties of soil.

Soil Strength

Soil strength is the ability of a soil to resist deformation. It is difficult to generalize about the strength of soils. Numerical averages of the strength of a soil can be misleading because soils are often composed of mixtures, zones, or layers of materials with different physical and chemical properties.

The strength of a particular soil type is a function of cohesive and frictional forces. *Cohesion* is a measure of the ability of very small silt and clay soil particles to stick together. The cohesion of particles in fine-grained soils is primarily the result of electrostatic forces between particles and is a significant factor in determining the strength of a soil. In partially saturated coarse-grained, sandy soils, moisture films between the grains may cause an apparent cohesion due to surface tension caused by the attraction of water molecules to each other at the surface or between soil grains (Figure 17.7). The principle of cohesion explains the ability of damp sand, which is cohesionless when dry, to stand in vertical walls in sand castles on the beach (**Figure 17.8**).[15] Friction between grains also contributes to the strength of a soil. The total frictional force is a function of the density, size, and shape of the soil particles and of the weight of overlying particles that force the grains together. Frictional forces are most significant in coarse-grained soils rich in sand and gravel. Because of frictional forces, you do not sink far into the sand when walking on dry sand on beaches. Most soils are a mixture of coarse and fine particles, so the strength is usually a result of both cohesion and internal friction. Although it is difficult to generalize, clay-rich soils with weak clay minerals and organic-rich soils, such as peaty soils, tend to have lower strengths than coarser soils.

Vegetation may play an important role in soil strength. For example, tree roots may provide considerable cohesion through the binding characteristics of a continuous root mat or by anchoring individual roots to bedrock beneath thin soils on steep slopes (**Figure 17.9**).

Soil Sensitivity

Soil sensitivity measures changes in soil strength resulting from disturbances such as vibrations or excavations. Sand and gravel soils with no clay are the least sensitive. As fine material becomes abundant, soils become more and more sensitive. Some clay soils may lose 75 percent or more of their strength after a disturbance.[16]

FIGURE 17.8 Apparent cohesion Sand castle. The surface tension of water molecules in the damp sand enables the walls of the castle to stand. *(Brasil2/iStockphoto)*

FIGURE 17.9 Root strength Tree roots are helping to bind the particles of this riverbank soil together. *(Edward A. Keller)*

Soil Compressibility

Soil compressibility is a measure of a soil's tendency to consolidate, or decrease in volume. Compressibility is partially a function of the elastic nature of the soil particles and is directly related to the settling of structures, such as the world-famous Leaning Tower of Pisa in Italy (**Figure 17.10**). Excessive settling will crack foundations and walls. Coarse materials, such as gravels and sands, have a low compressibility, and settling will be considerably less in these materials than in highly compressible fine-grained or organic soils.

FIGURE 17.10 Leaning Tower of Pisa, Italy The lean is a result of differential settling of the soil. If correction measures had not been taken to strengthen the tower, it would have fallen over. *(stevenallan/iStockphoto)*

Erodibility

Soil *erodibility* refers to the ease with which soil materials can be removed by wind or water. Soils with a high erosion factor include unprotected silts and sands. Cohesive soils, which are more than 20 percent clay, naturally cemented soils, and coarse gravel-rich soils are not as easily eroded by wind or water and, therefore, have a low erosion factor.

Hydraulic Conductivity

Hydraulic conductivity (K) is a measure of the ease with which water moves through a material. Hydraulic conductivity is measured in units of velocity, centimeters per second, or centimeters per hour (see the discussion of groundwater in Chapter 13). Saturated clean gravels or sands have the highest K values (from 5 to greater than 50 cm per hour [2 to

greater than 20 in. per hour]). As fine particles in a saturated mixture of clean gravel and sand increase, K decreases. Saturated clays generally have a very low K, less than 0.025 cm (0.01 in.) per hour.[9] Hydraulic conductivity in unsaturated soils is complex; fine-grained, unsaturated soils actually pull or suck water and hold it tightly. Hydraulic conductivity is very important in many soil environmental problems related to soil drainage, the movement of liquid pollutants in soils, and land use potential for agriculture, waste disposal, and construction.

Corrosion Potential

Corrosion is a slow weathering or chemical decomposition that proceeds from the surface into the ground. All objects buried in the ground—pipes, cables, anchors, and fence posts, for example—are subject to corrosion. The corrosiveness of a particular soil depends on the chemistry of the soil, the buried material, and the amount of water available.[17]

Ease of Excavation

Ease of excavation pertains to the procedures, and hence the equipment, required to remove soils during construction. There are three general categories of excavation techniques. *Common excavation* is accomplished with an earth mover, a backhoe, or a bulldozer. This equipment essentially removes the soil without having to scrape it first; most soils can be removed by this process. *Rippable excavation* requires breaking up the soil with special ripping teeth before it can be removed. For example, a tightly compacted or cemented soil would require rippable excavation. *Blasting* or *rock cutting* is the third, and often the most expensive, category; a hard, silica cemented soil might need to be cut with a jackhammer before being removed.

Shrink–Swell Potential

Shrink–swell potential refers to the tendency of a soil to gain or lose water. Soils that tend to increase or decrease in volume with water content are called **expansive soils**. The swelling is caused by the chemical attraction of water molecules to the submicroscopic flat particles, or plates, of certain clay minerals. The plates are composed primarily of silica, aluminum, and oxygen atoms, and layers of water are added between the plates as the clay expands or swells (**Figure 17.11a**).[18] Expansive soils tend to absorb large quantities of water and expand. Cracks in the ground form when the soil dries out and contracts (Figure 17.11c). *Montmorillonite* is the common clay mineral associated with most expansive soils. With sufficient water, pure montmorillonite may expand up to 15 times its original volume; fortunately, most soils contain limited amounts of this clay mineral, so it is unusual for an expansive soil to swell beyond 25 to 50 percent. However, an increase in volume of more than 3 percent is considered potentially hazardous.[18]

Expansive soils in the United States cause significant environmental problems. As one of our most costly natural hazards, expansive soils are responsible for several billions of dollars in damages annually to highways, buildings, and other structures. Every year, more than 250,000 new houses are constructed on expansive soils. Of these, about 60 percent will experience some minor damage, such as cracks in the foundation, walls, driveway, or walkway (Figure 17.11b,d); 10 percent will be seriously damaged, some beyond repair.[19,20]

Structural damage on expansive soils is caused by volume changes in the soil in response to changes in moisture content. Factors that affect the moisture content of an expansive soil include climate, vegetation, topography, drainage, and quality of construction.[19] Builders in regions that have a pronounced wet season followed by a dry season allow for a regular shrink–swell sequence. These regions, such as the southwestern United States, are more likely to experience an expansive soil problem than are regions where precipitation is more evenly distributed throughout the year. Vegetation can cause changes in the moisture content of soils. Because large trees draw and use a lot of local soil moisture, especially during a dry season, they facilitate soil shrinkage. Therefore, in areas with expansive soil, trees should not be planted close to the foundations of light structures, such as homes (Figure 17.11b).

Topography and drainage are also significant factors for evaluating expansive soils. Adverse topographic and drainage conditions cause water to form ponds around or near structures, increasing the swelling of expansive clays. However, homeowners and contractors can do a great deal to avoid this problem. Proper design of subsurface drains and rain gutters can minimize expansive soil damages by improving drainage, as may designing and constructing foundations to accommodate some shrinking and swelling of the soil.[19]

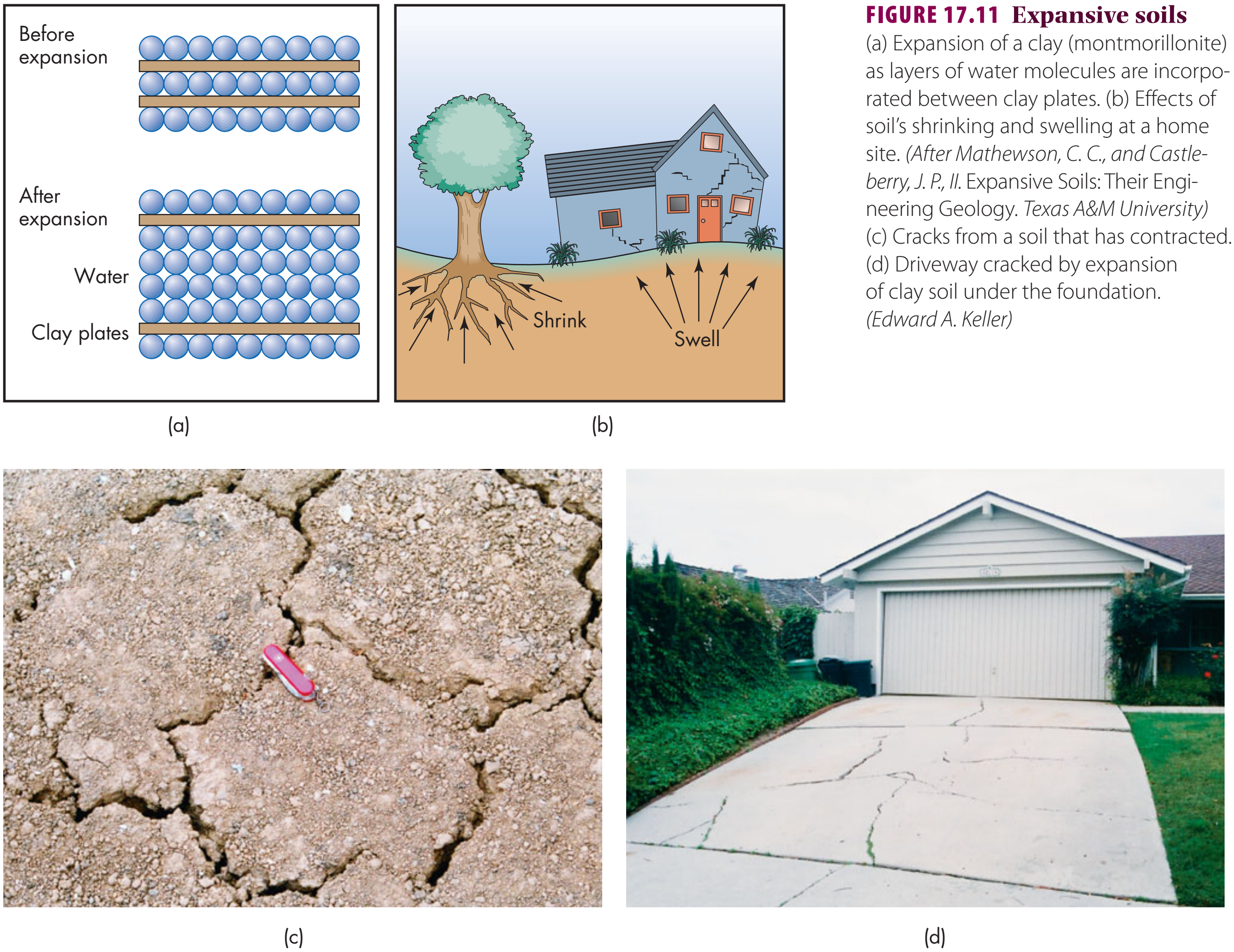


FIGURE 17.11 Expansive soils (a) Expansion of a clay (montmorillonite) as layers of water molecules are incorporated between clay plates. (b) Effects of soil's shrinking and swelling at a home site. *(After Mathewson, C. C., and Castleberry, J. P., II.* Expansive Soils: Their Engineering Geology. *Texas A&M University)* (c) Cracks from a soil that has contracted. (d) Driveway cracked by expansion of clay soil under the foundation. *(Edward A. Keller)*

Clearly, some soils are more desirable than others for specific uses. Although planners concerned with land use will not conduct soil tests to evaluate the engineering properties of soils, they will be better prepared to take advantage of geologic conditions if they understand the basic terminology and principles of Earth materials. Our discussion of engineering properties established two general principles. First, because of their low strength, high sensitivity, high compressibility, low permeability, and variable shrink–swell potential, clay soils should be avoided in projects involving heavy structures, structures with minimal allowable settling, or projects needing well-drained soils. Second, soils that have a high corrosive potential or that require other than common excavation should be avoided if possible. If such soils cannot be avoided, extra care, special materials and techniques, and higher-than-average initial costs—including planning, design, and construction—must be expected. The secondary costs—that is, the operation and maintenance costs of these projects—may also be greater.

17.8 Rates of Soil Erosion

Rates of soil erosion are measured as a volume, mass, or weight of soil that is removed from a location within a specified time and area, such as kilograms per year per hectare. Soil erosion rates vary with the engineering properties of the soil, land use, topography, and climate.

There are several approaches to measuring rates of soil erosion. The most direct method is to make actual measurements on slopes over a period of at least several years and use these values as representative of what is happening over a wider area and longer time

A Closer Look

The Universal Soil Loss Equation

The Universal Soil Loss Equation is

$$A = RELSCP$$

where

A = long-term *average* annual soil loss for the site being considered

R = long-term rainfall *runoff* erosion factor

E = soil erodibility index

L = hillslope/*length* factor

S = hillslope/gradient, or *slope* factor

C = soil *cover* factor

P = erosion-control *practice* factor

The advantage of using this equation is that, once the various factors have been determined and multiplied together to produce predicted soil loss, conservation practices may be applied through factors C and P to reduce the soil loss to the desired level. For slopes that are amenable to shaping, factors E, L, and S may also be manipulated to achieve desired sediment loss results. This equation is particularly valuable for evaluating construction sites and areas along corridors, such as pipelines and highways. When planning construction sites, planners can use the Universal Soil Loss Equation to predict the impact of sediment loss on local streams and other resources and to develop management strategies for minimizing this impact.[21,22]

span. This approach is rarely used, however, because data from individual slopes and drainage basins are very difficult to obtain. A second approach is to use data obtained from resurveying reservoirs to calculate the change in the reservoirs' storage capacity of water; the depletion of storage capacity is equivalent to the volume of sediment eroded from upstream soils. A third approach is to use an equation to calculate rates of sediment eroded from a particular site. One of the most commonly used equations is the Universal Soil Loss Equation.[21] This equation uses data on rainfall, runoff, the size and shape of the slope, the soil cover, and erosion-control practices to predict the amount of soil moved from its original position[22] (see A Closer Look: The Universal Soil Loss Equation).

FIGURE 17.12 Serious soil erosion Gully formation in central California related to diversion of runoff water. The surface was essentially ungullied several months before the photograph was taken. *(Edward A. Keller)*

17.9 Sediment Pollution

Sediment is one of our greatest pollutants. In many areas, it chokes streams; fills in lakes, reservoirs, ponds, canals, drainage ditches, and harbors; buries vegetation; and generally creates a nuisance that is difficult to remove. Natural pollutional sediment—eroded soil—is truly a resource out of place. It depletes soil at its site of origin (Figure 17.12), reduces the quality of the water it enters, and may deposit unwanted sediment on productive croplands or other useful land (Figure 17.13).[23]

Sources of the sediment include land disturbed for agriculture; land overgrazed by animals, such as sheep or cattle; urban construction sites; land recently

Case History

Reduction of Sediment Pollution, Maryland

A study in Maryland demonstrated that sediment control measures can reduce sediment pollution in an urbanizing area.[24] The suspended sediment transported by the northwest branch of the Anacostia River near Colesville, Maryland, with a drainage area of 55 km^2 (21 mi^2), was measured over a 10-year period. During that time, construction within the basin involved about 3 percent of the area each year. The total urban land area in the basin was about 20 percent at the end of the 10-year study.

Sediment pollution was a problem in the area because the soils are highly susceptible to erosion; moreover, there is sufficient precipitation to ensure their erosion when construction has removed the vegetative cover. Most of the sediment is transported during spring and summer rainstorms.[24] A sediment-control program was initiated, and the sediment yield was reduced by about 35 percent. The program utilized basic sediment-control principles, such as tailoring development to the natural topography, exposing a minimal amount of land, providing protection for exposed soil, minimizing surface runoff from critical areas, and trapping eroded sediment on construction sites. Specific measures included scheduled grading to minimize the time of soil exposure, mulch application and temporary vegetation to protect exposed soils, sediment diversion berms, stabilized channels, and sediment basins. The Maryland study concluded that even further sediment control can be achieved by both scheduling major grading during periods of low erosion potential and designing improved sediment traps to control runoff during storms.[24]

FIGURE 17.13 Unwanted sediment Soil erosion has resulted in unwanted red sediment at this site in Charlotte, North Carolina. *(Edward A. Keller)*

logged or burned; and land disrupted by mining. **Sediment pollution** affects rivers, streams, lakes, and even the ocean. Unfortunately, the problem promises to be with us indefinitely. One solution to sediment pollution is to implement sound conservation practices, particularly in urbanizing areas where tremendous quantities of sediment are produced during construction (see Case History: Reduction of Sediment Pollution, Maryland). Another solution is to use sediment control basins, which are designed to trap and control sediment; they must be periodically cleared out to operate effectively. A generalized cross section of a sediment control basin is shown in Figure 17.14.

17.10 Land Use and Environmental Problems of Soils

Human activities affect soils by influencing the pattern, amount, and intensity of surface-water runoff, erosion, and sedimentation. The most important of these human influences is the conversion of natural areas to various land uses.

The estimated and observed variation in sediment yield that accompanied changes in land use in the Piedmont region from 1800 to 2000 are summarized in Figure 17.15. Notice the sharp peak in sediment production during the construction phase of urbanization in about 1960. These data suggest that the effects of land use change on a drainage basin, its streams, and its sediment production may be quite dramatic. Streams and

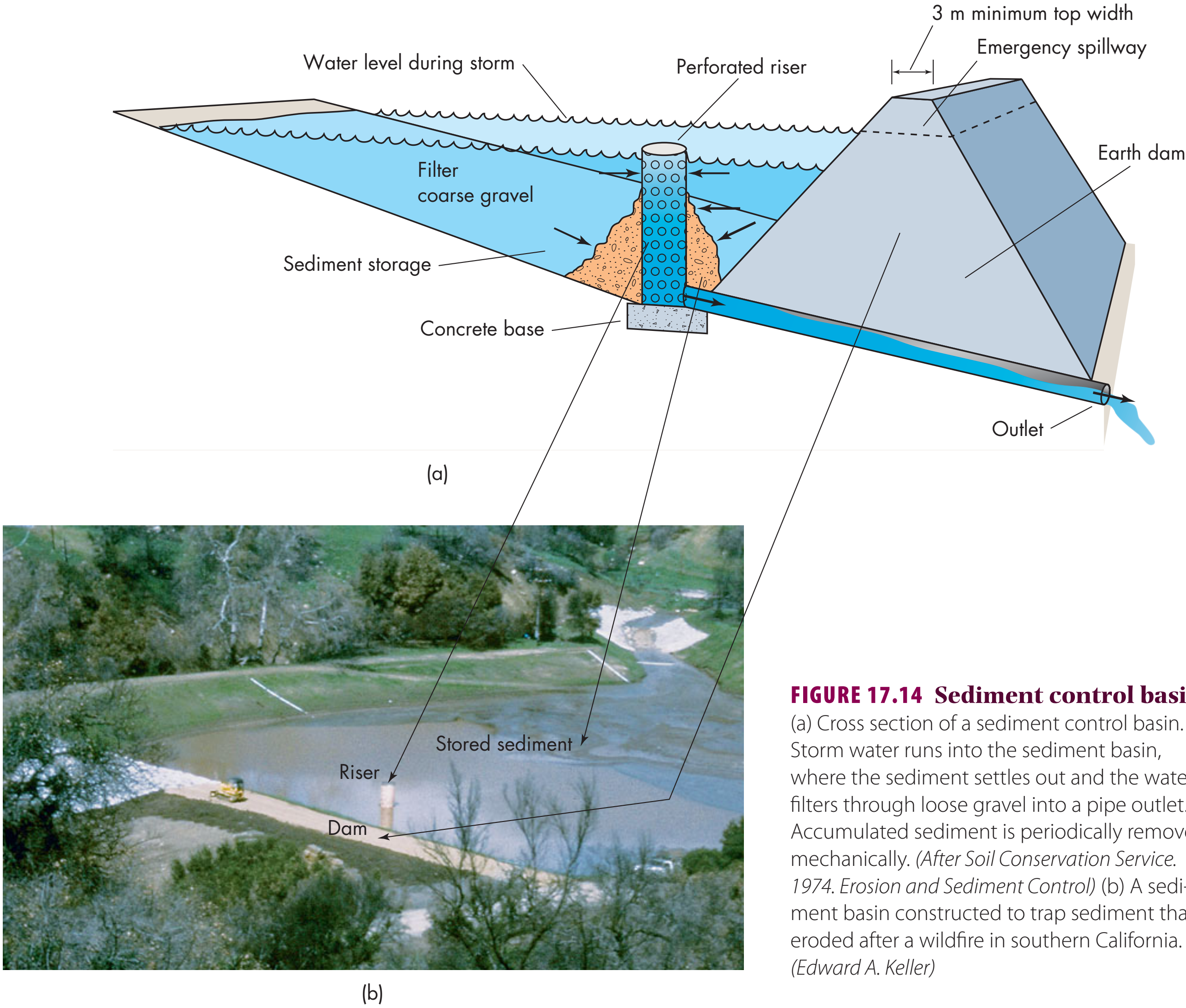


FIGURE 17.14 Sediment control basin (a) Cross section of a sediment control basin. Storm water runs into the sediment basin, where the sediment settles out and the water filters through loose gravel into a pipe outlet. Accumulated sediment is periodically removed mechanically. *(After Soil Conservation Service. 1974. Erosion and Sediment Control)* (b) A sediment basin constructed to trap sediment that eroded after a wildfire in southern California. *(Edward A. Keller)*

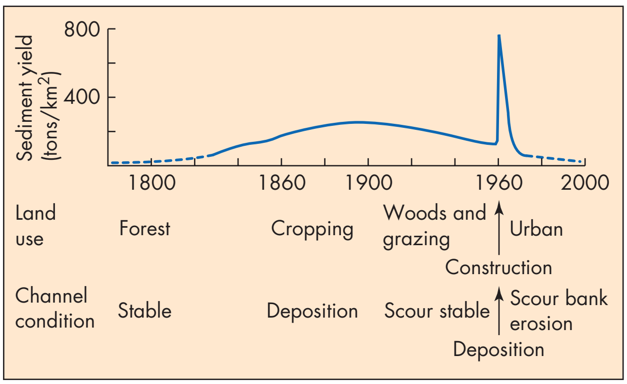


FIGURE 17.15 Land use and sediment yield Effect of land use on sediment yield and channel condition. The graph shows observed and estimated changes in the Piedmont region of the eastern United States, from before the beginning of extensive farming through a period of construction and urbanization (200 tons per km^2 = 500 tons per mi^2). *(After Wolman, M. 1966. Geografiska Annaler 49A)*

naturally forested areas are assumed to be relatively stable (i.e., without excessive erosion or deposition). A land use change that converts forested land to agricultural purposes also generally increases runoff and erosion. As a result, streams become muddy and may not be able to transport all the sediment delivered to them. The channels will, therefore, partially fill with sediment, or *aggrade*, possibly increasing the magnitude and frequency of flooding.

Agriculture

In the past 50 years, soil erosion and overuse of soils caused by intensive agriculture have damaged about 10 percent of the world's best agricultural land. It is estimated that, in the United States, approximately one-third of the *topsoil*, the most fertile soil near the

FIGURE 17.16 Contour plowing Contour plowing can significantly reduce soil erosion. This scene is near McGregor, Iowa. *(Alex S. MacLean/Peter Arnold, Inc.)*

surface that supports vegetation, has been lost to erosion.[5,25]

Traditional agriculture, which involves plowing the soil in straight lines, or furrows, is particularly damaging. Removal of vegetation exposes the soil to erosion by wind and water. Even on gentle slopes, furrows may channel the water downslope, increasing the erosion potential. Although new soil is constantly forming, soils form very slowly, from a rate of about 1 mm (0.04 in.) in several decades to as much as 1 mm (0.04 in.) per year. The key to sustaining soil resources is to reduce erosion to a rate less than the rate at which soils naturally form. Some practices to sustain soils include:[25]

- ***Contour plowing.*** This involves plowing with the natural topography of the land. Furrows are plowed perpendicular to the slope of the land rather than in the downslope direction. This is one of the most effective ways to reduce erosion by running water and is widely used (**Figure 17.16**).
- ***No-till agriculture.*** This system eliminates plowing altogether, greatly reducing soil erosion. No-till agriculture is an integrated plan to plant and harvest crops without plowing while suppressing weeds and other pests.
- ***Terracing slopes.*** Soil erosion on steep slopes can be managed and minimized by terracing slopes to produce flat areas for farming. Retaining walls of stone or other materials are used to form terraces and stabilize the slope. Terracing is widely used on farms around the world (**Figure 17.17**).
- ***Planting of more than one crop.*** This method is most effective on small farms in the tropical rain forest and other areas. The forest trees are cut in small patches of land, and some smaller trees and plants are left in place. Several crops are planted among the remaining natural vegetation (**Figure 17.18**). After several years, the land is allowed to recover. When the forest has grown back, the process may be repeated. This approach works if human population on the land is low. With increased population and pressure to farm more land more frequently, the practice is not sustainable.

Urbanization

The conversion of agricultural, forested, or rural land to highly urbanized land causes dramatic changes. During the construction phase of a conversion, there is a tremendous increase in sediment

FIGURE 17.17 Terraced slopes Terraces reduce soil erosion and produce flat land for farming. These rice paddies on terraces are in Bali, Indonesia. *(asiafoto/iStockphoto.)*

production, which may be accompanied by a moderate increase in runoff (Figures 17.15 and 17.19). The response of streams in the area is complex and may include both channel erosion and deposition, resulting in wide, shallow channels. The combination of increased runoff and shallow channels increases the flood hazard. After the construction phase, the land is mostly covered with buildings, parking lots, and streets, so the sediment yield drops to a low level. Streams respond to the lower sediment yield and higher runoff by eroding their channels, which become deeper. However, because of the large impervious areas and the use of storm sewers, runoff increases, again increasing the risk of flooding.

The process of urbanization directly affects soils in several ways:

FIGURE 17.18 Multiple crops Farming a small plot of land in the rain forest of Nigeria, producing several crops. *(Still Pictures/Peter Arnold, Inc.)*

- Soil may be scraped off and lost. Once sensitive soils are disturbed, they may have lower strengths when they are remolded.
- Materials may be brought in from outside areas to fill a depression before construction, resulting in a much different soil than was previously there.
- Draining soils to remove water may cause *desiccation*, or drying out, and other changes in soil properties.
- Soils in urban areas are susceptible to soil pollution resulting from deliberate or inadvertent addition of chemicals to soils. This problem is particularly serious if hazardous chemicals have been applied.

Off-Road Vehicles

Urbanization is not the only land use that causes increased soil erosion and hydrologic changes. In recent years, the popularity of off-road vehicles (ORVs) has increased enormously; demand for recreational areas to pursue this interest has led to serious environmental problems, as well as conflicts between users of public lands.

There are now millions of ORVs, many of which are invading the deserts, coastal dunes, and forested mountains of the United States. Problems associated with ORVs are common, from the shores of North Carolina and New York to sand dunes in Michigan and Indiana to deserts and beaches in the western United States. A single motorcycle need travel only 8 km (5 mi) to have an impact on an area measuring 1,000 m^2 (10,765 ft^2), and a four-wheel-drive vehicle has an impact over the same area by traveling only 2.4 km (1.5 mi). In some desert areas, the tracks produce scars that may remain part of the landscape for hundreds of years.[26,27]

The major areas of environmental problems caused by ORVs are soil erosion, changes in hydrology, and damage to plants and animals. Off-road vehicles cause direct mechanical erosion and facilitate wind and water erosion of materials loosened by their passing

FIGURE 17.19 Soil erosion in the urban environment (a) Urbanization and the construction of freeway on-ramps can contribute to soil erosion and increased sediment production. This eroding embankment is near the University of California, Santa Barbara, and the community of Isla Vista. (b) A few years after erosion control measures were taken by planting vegetation. *(Edward A. Keller)*

(Figure 17.20). Runoff from ORV sites is as much as eight times greater than for adjacent, unused areas, and sediment yields are comparable to those found on construction sites in urbanizing areas.[27] Hydrologic changes from ORV activity result primarily from near-surface soil compaction that reduces the ability of the soil to absorb water. Furthermore, water already in the soil becomes more tightly held and, thus, less available to plants and animals. In the Mojave Desert, tank tracks produced 50 years ago are still visible, and

(a)

(b)

FIGURE 17.20 Off-road vehicles Serious erosion problems caused by off-road vehicle use (a) in mountains and (b) on coastal dunes. *(Edward A. Keller)* (c) An ORV churning up sand on a coastal dune. *(Steve Osman/Los Angeles Times)*

(c)

the compacted soils have not recovered.[27] Compaction also changes the variability of soil temperature. This effect is especially apparent near the surface, where the soil becomes hotter during the day and colder at night. Animals are killed or displaced, and vegetation is damaged or destroyed by intensive ORV activity. The damage results from a combination of soil erosion, compaction, temperature change, and moisture content change.[27]

There is little doubt that as a management strategy, some land must be set aside for ORV use. However, how much land should be involved, and how can environmental damage be minimized? Sites should be chosen in closed basins with minimal soil and vegetation variation. The possible effects of erosion by wind must be evaluated carefully, as must the sacrifice of nonrenewable cultural, biological, and geologic resources.[26] A major problem remains: Intensive ORV use is incompatible with nearly all other land use, and it is very difficult to restrict damages to a specific site. Material removed by mechanical, water, and wind erosion will always have an impact on other areas and activities.[26,27]

In recent years, the demand for self-propelled vehicles has been increasing. Use of off-road mountain bikes has grown dramatically and is having an impact on the environment. Bicycles have damaged mountain meadows, and their intensive use contributes to trail erosion (**Figure 17.21**). Mountain bike users are lobbying to gain entry into even more locations in the national forests, parks, and wilderness areas. Their position is that one bicycle causes less erosion than one horse. Although this is generally true, mountain bikes are cheaper and easier to maintain than horses; therefore, there are many more people riding mountain bikes than there are riding horses. Thus, the cumulative effect of bicycles on trails may be greater than that of horses. Also, hikers and other visitors may not mind seeing animals such as horses in wilderness areas but may be less receptive to bicycles, which are fast and almost silent (you can't hear them coming). Wilderness management plans will have to be developed to ensure that overenthusiastic people do not damage sensitive environments.

FIGURE 17.21 Soil erosion due to biking and walking caused loss of vegetation and increased runoff that excavated ruts about 1 m (3 ft) deep by in a sandy soil at this coastal California site. *(Edward A. Keller)*

17.11 Soil Pollution

Soil pollution occurs when materials detrimental to people and other living things are inadvertently or deliberately applied to soils (see Case History: Times Beach, Missouri, at the beginning of this chapter). Many types of materials, including organic chemicals, such as hydrocarbons or pesticides, or heavy metals, such as selenium, cadmium, nickel, or lead, may act as soil contaminants. Soils, particularly those with clay particles, can also act to selectively attract, absorb, or bind toxins and other materials that otherwise would contaminate the environment. Soils may also contain organisms that break down certain contaminants into less harmful materials. As a result, soils offer opportunities to reduce environmental pollution. However, contaminants in soils and the products of their breakdown by soil and biochemical processes may be toxic to ecosystems and humans if they become concentrated in plants or are transported into the atmosphere or water.[8]

Problems arise when soils intended for uses other than waste disposal are contaminated or when people discover that soils have been contaminated by previous uses. Houses and other structures, such as schools, have been built over sites where soils have been contaminated. At many sites, contamination from old waste-disposal facilities or from dumping of chemicals is now being discovered; some of these sites are being treated. However, treatment of soils to remove contaminants can be a very costly endeavor. Treatments vary from excavation and disposal to incineration or bioremediation. Often, bioremediation is done on the pollution site and does not require excavating and moving large quantities of contaminated soil (**Figure 17.22**).[8,28] In recent years, soil and water contaminated by leaking underground tanks have become a significant environmental concern. Businesses are now adding systems to monitor storage tanks so that leaks can be detected before significant environmental damage occurs.

17.12 Soil Surveys and Land Use Planning

The best use of land is greatly determined by its soils; therefore, a report called a **soil survey** is an important part of planning for nearly all engineering projects. A *soil survey* should include soil descriptions; soil maps showing the horizontal and vertical extent of soils; and results of tests to determine grain size, moisture content, and strength. The

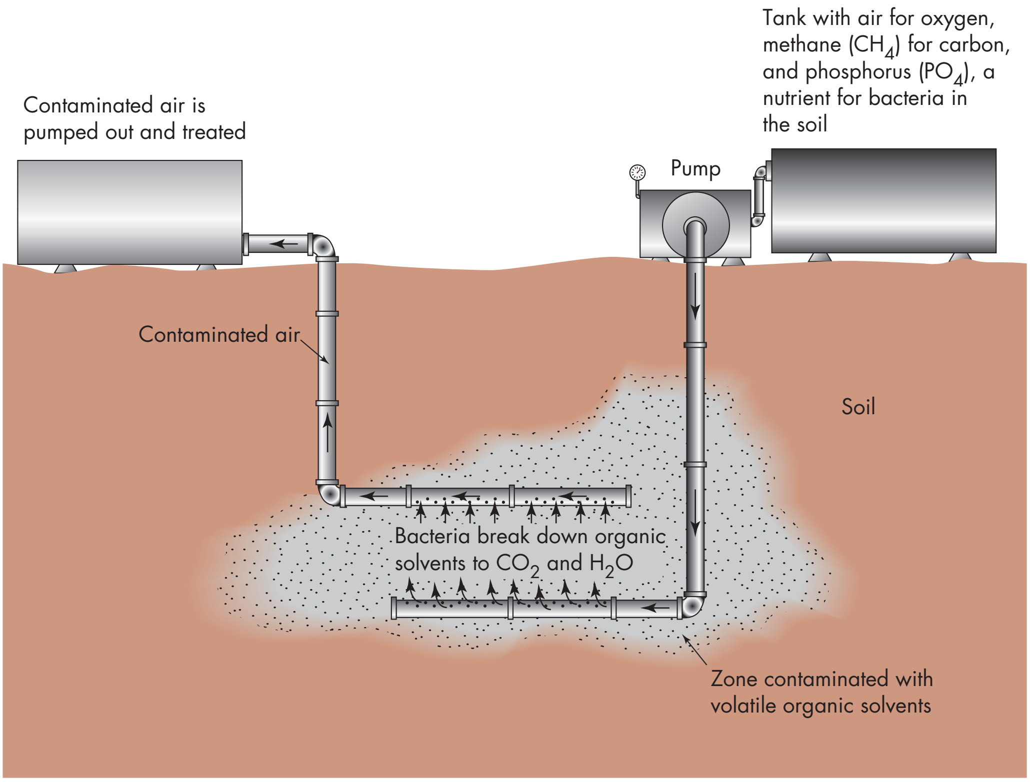


FIGURE 17.22 Bioremediation Idealized diagram illustrating the process of enhanced bioremediation of soil contaminated by an organic solvent. Methane (CH_4), phosphorus (PO_4), and air (with O_2) are nutrients pumped intermittently into the contaminated area and released from the lower slotted pipe. The upper pipe (also slotted) sucks contaminated air from the soil. The nutrients stimulate the growth of bacteria. The supply of methane, a carbon source, is then stopped, and the carbon-hungry bacteria go after the inorganic solvents, degrading them to carbon dioxide and water as part of their life cycle. This type of process can significantly reduce the time and cost involved in treating the contaminated soil. *(Modified after Hazen, T. C. 1995. Savanna River site—A test bed for cleanup technologies.* Environmental Protection, *April, 10–16)*

purpose of a soil survey is to provide necessary information for identifying potential problem areas before construction.[9]

The information from detailed soil maps can be extremely helpful in land use planning if it is used in combination with guidelines for the proper use of soils. Soils can be rated according to their limitations for a specific land use, such as housing, light industry, septic-tank systems, roads, recreation, agriculture, and forestry.

Making The Connection

Linking the Opening Case History About Times Beach to the Fundamental Concepts

Consider and discuss the following questions:

1. What were the impacts of population increase on soil pollution at Times Beach?
2. Why is the understanding of soils important for understanding what happened at Times Beach?
3. How do science and values link to what happened at Times Beach?

Summary

Engineers define soil as Earth material that may be removed without blasting; to a soil scientist, a soil is solid Earth material that can support rooted plant life. A basic understanding of soils and their properties is becoming crucial in several areas of environmental geology, including land-use planning, waste disposal, and evaluation of natural hazards, such as flooding, landslides, and earthquakes.

Soils result from interactions of the rock and hydrologic cycles with biogeochemical processes. As open systems, they are affected by variables, such as climate, topography, parent material, time, and biological activity. Soil-forming processes tend to produce distinctive soil layers, or horizons, defined by the processes that formed them and the type of materials present. The processes of leaching, oxidation, and accumulation of materials in various soil horizons are particularly important. Development of the argillic B horizon, for example, depends on the translocation of clay minerals from upper to lower horizons. Three important properties of soils are color, texture or particle size, and structure (i.e., the aggregation of particles).

A soil may be considered a complex ecosystem in which many types of living things convert soil nutrients into forms that plants can use. Soil fertility is the capacity of soil to supply nutrients needed for plant growth. Soils may go through natural stages of building, sustaining, and degrading. Each stage has important implications for ecosystems.

Soil has a solid phase consisting of mineral and organic matter; a gas phase, including mostly air; and a liquid phase, which consists mostly of water. Water may flow vertically or laterally through the pores of a soil. The flow is either saturated, with all pore space filled with water, or, more commonly, unsaturated, with pore spaces partially filled with water. Soil moisture and how water moves through soils are becoming important topics in environmental geology.

Several types of soil classification exist, but none of them integrates both engineering properties and soil processes. Environmental geologists must be aware of both the soil-science classification, or soil taxonomy, and the engineering classification, known as the unified soil classification system.

A basic understanding of the engineering properties of soils is crucial in many environmental problems. These properties include soil strength, sensitivity, compressibility, erodibility, hydraulic conductivity, corrosion potential, ease of excavation, and shrink–swell potential. Shrink–swell potential is particularly important because expansive soils in the United States cause significant environmental problems and constitute one of our most costly natural hazards.

Soil erosion is one of our most serious environmental problems linked to food supply. Rates of soil erosion can be determined by direct observation of soil loss from slopes, by measurement of accumulated sediment in reservoirs, or by calculation using an equation. A common method is to apply the Universal Soil Loss Equation, which uses variables that affect erosion to predict the amount of soil that will be moved from its original position. These variables can often be manipulated as part of a management strategy to minimize erosion and sediment pollution from a particular site. Sediment, both natural and human-made, may be one of our greatest pollutants. It reduces water quality and chokes streams, lakes, reservoirs, and harbors. With good conservation practices, sediment pollution can be greatly reduced.

Sustaining soils requires that rates of soil erosion be less than rates of soil formation. Land use and surface-water manipulation affect the pattern, amount, and intensity of surface-water runoff, soil erosion, and sediment pollution. In agricultural areas, soil erosion may be minimized most effectively by contour plowing, no-till agriculture, slope terracing, and planting of more than one crop.

Urbanization often involves loss of soil, changes of soil properties, acceleration of soil erosion during construction, and pollution of soils. Use of motorized and non-motorized off-road vehicles causes soil erosion, changes in hydrology, and damage to plants and animals.

Soil pollution occurs when hazardous materials are inadvertently or deliberately added to soils. Pollution limits the usefulness of soils or even renders them hazardous to life. Processes in soils may also be useful in reducing or eliminating contaminants from soil. The deliberate use of soil processes to eliminate contamination is known as bioremediation.

Soil surveys are extremely useful in land use planning. Soils can be rated according to their limitations for various land uses. This information can be combined with a detailed soils map to produce a simplified map that shows a soil's limitations for a specific use.

Revisiting Fundamental Concepts

Human Population Growth

Increases in human population have resulted in a need for more soil resources to grow food to support our growing numbers; they have also resulted in productive soils formerly used for agriculture being covered with pavement and buildings. Intensive agriculture to provide food for

the world's growing population has required the use of tremendous amounts of chemical fertilizers and water for irrigation in semiarid and arid regions. These practices have resulted in an increase in soil and water pollution from the use of chemical fertilizers.

Sustainability Sustaining soil resources is one of the fundamental goals to ensure long-term food production in agricultural regions. Of particular importance is the development of plans to minimize soil erosion that results in loss of soil resources and produces sediment pollution.

Earth as a System Soils are complex ecosystems involving interactions between the hydrologic and rock cycles and biogeochemical processes through time. As climate changes, so do soil-forming processes, and soils often reflect climatic changes that alter patterns of precipitation and the amount of solar energy received at the surface of Earth.

Hazardous Earth Processes, Risk Assessment, and Perception Loss of soil fertility as a result of soil erosion and other processes is a serious hazard with respect to our ability to provide food to feed the people of the world. In addition, specific soil hazards exist, including the shrink–swell properties of soils, that may cause damage to roads, buildings, and other structures.

Scientific Knowledge and Values The study of soils is a mature science, and we have a good understanding of how soils form, are eroded, and may be sustained. Pollution of soils is a serious problem in agricultural and urban areas. How we ultimately deal with soil pollution will reflect our values concerning the rights of people to live in an environment where soils do not produce health hazards as a result of pollution.

Key Terms

expansive soil (p. 601)
relative profile development (p. 594)
sediment pollution (p. 604)
shrink–swell potential (p. 601)
soil (p. 588)
soil chronosequence (p. 594)
soil fertility (p. 595)
soil horizon (p. 590)
soil profile (p. 590)
soil survey (p. 610)

Review Questions

1. Differentiate how we define *soil* from a soil scientist's perspective and that of an engineer.
2. What is the difference between a residual and a transported soil?
3. What are the major soil horizons?
4. Define *soil texture*.
5. What do we mean by soil fertility?
6. What are the two major ways that we classify soils?
7. What determines the strength of a soil?
8. What is the shrink–swell potential of a soil, and why is knowing this important?
9. What are some of the ways that we can evaluate rates of soil erosion?
10. Why is sediment pollution such a large environmental problem?
11. What is the role of urbanization in causing soil erosion, and how can it be minimized?
12. How has the use of motorized and non-motorized off-road vehicles caused soil erosion problems?
13. How can soil pollution occur?
14. What is a soil survey, and how can it be used in land-use planning?

Critical Thinking Questions

1. Defend the statement that soil erosion is an environmental problem that could seriously damage, or even cause the collapse of, our civilization.

2. How and why could processes such as clear-cut logging, in which all trees are cut, and use of off-road vehicles lead to loss of soil fertility?

3. One of your environmentalist friends really likes to ride her mountain bike on steep terrain. She particularly likes racing downhill on ski slopes during the summer. What are some conflicts she may have in reconciling her sport with potential damage to the environment?

4. You own a consulting firm, and a client hires you to evaluate several hundred hectares (acres) to start a small farm to grow organic vegetables. The land is generally flat, with some rolling hills. How could you evaluate the project from a soils perspective? Outline a general plan to advise your client.

Companion Website

www.mygeoscienceplace.com

PEARSON mygeoscience place™ *Introduction to Environmental Geology, 5e* premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

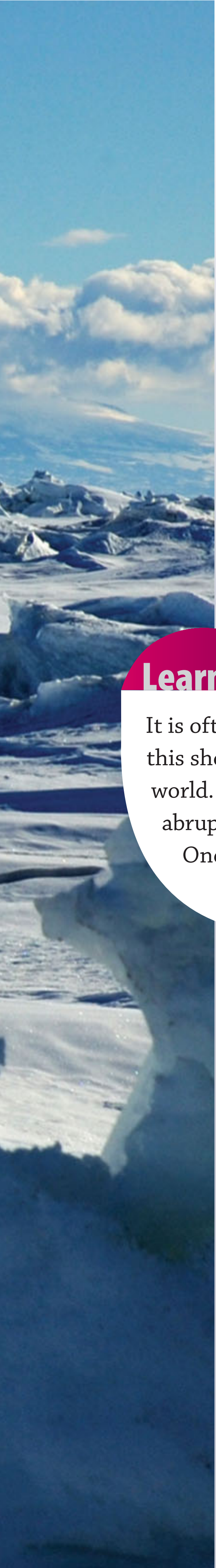
Part 4

Environmental Management, Global Perspective, and Society

Part 4 focuses on environmental geology and its relationship to society on local, regional, and global scales. We begin in Chapter 18 with a discussion of global climate change and present important topics, including (1) tools for studying global change, (2) Earth's atmosphere and climate change, (3) the potential effects of global climate change, and (4) the hypothesis that human activity causing emissions of greenhouse gases (primarily carbon dioxide) is resulting in global warming. The global mean annual temperature has increased about 0.8°C during the twentieth century, and from the 1990s to 2010 we experienced some of the warmest years on record. We conclude that global warming is occurring, and there is a human component of the warming produced by burning fossil fuels.

The "capstone" for this fifth edition of *Introduction to Environmental Geology* is a discussion of relationships between geology, society, and the future. Most professional geologists interact with society through their work in areas such as engineering and environmental geology, petroleum geology, economic geology, groundwater geology, geography, education, or research. Our work also has significant links with ecology. Chapter 19 discusses examples of how geology interacts with society, including environmental health, air pollution, waste management, environmental impact analysis, land use planning, and environmental law. A main conclusion is that if we are going to achieve sustainability, we need to carefully consider important links between geologic processes, the environment, and society. For example, we are just beginning to understand more fully the relationship between our geologic environment and human health and the incidence of chronic and acute diseases, including heart disease and cancer. The subjects of environmental impact analysis and land use planning are important because our approach to these subjects reflects our commitment to the environment at all levels. The important field of environmental law is assisting us in problem solving and mediation rather than confrontation and adversarial positions when dealing with environmental matters. Finally, Chapter 19 discusses three important steps necessary to avoid a potential environmental crisis and how we might attain sustainability.

The arctic is changing. Warming in the arctic during the past few decades has been more rapid than at lower latitudes. *(Goddard Space Flight Center/NASA)*



18 Global Climate Change

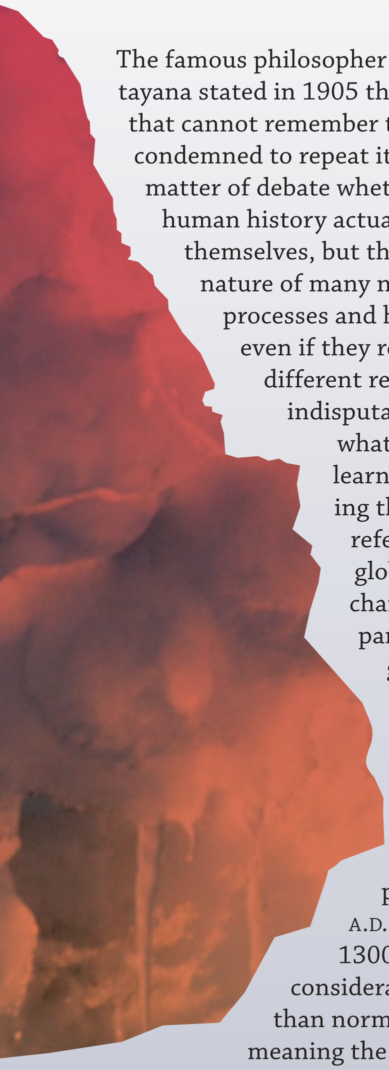
Learning Objectives

It is often said that the only certainties in life are death and taxes, but *change* could also be added to this short list. We are all interested in changes that will affect us, our families, our society, and the world. The sorts of changes we might encounter are many—varying from gradual to accelerating, abrupt, chaotic, and surprising. Some changes will affect our local, regional, or global environment. One change that affects all of us is global climate change. In this chapter, we will focus on the following learning objectives:

- **Know the tools used for studying Earth systems science and global change**
- **Understand the science of climate change and global warming**
- **Know some of the potential impacts of global warming and how they might be minimized**
- **Know how global climate change is linked to ozone depletion**

Case History

What Does Our Recent History Tell Us About Potential Consequences of Global Warming?



The famous philosopher George Santayana stated in 1905 that "those that cannot remember the past are condemned to repeat it." It is a matter of debate whether cycles in human history actually repeat themselves, but the repetitive nature of many natural processes and hazards, even if they result from different reasons, are indisputable. So, what can we learn by examining the past with reference to global climate change and, in particular, global warming? It turns out that, over an approximately 300-year period from A.D. 1000 to 1300, Earth was considerably warmer than normal (*normal* meaning the average surface temperature during the past century or some shorter interval, such as between 1961 and 1990). This period is known as the Medieval Warm Period (MWP), and we can possibly learn some lessons from that event. Although the MWP occurred only a few hundred years ago, we don't know much about it except that it was, in fact, warm and perhaps nearly as warm as our world today. Most scientists who study the indicators of past climate state that it probably wasn't quite as warm, but, certainly, parts of the world and, in particular, Western Europe and the North Atlantic, may have been warmer some of the time during the MWP than in the last decade of the twentieth century. During the MWP, there were winners and losers. In Western Europe, there was a flourishing of culture and activity, as well as an expansion of the population, as harvests were plentiful and people generally prospered. During that period, many of Europe's grand cathedrals were constructed.[1–3] Finally, during the MWP, the first global trade routes opened from Europe to China, connected by favorable climate and camel caravans.

During the MWP, sea temperatures in the North Atlantic evidently were warmer, and there was less sea ice. The famous Viking explorer Erik the Red embarked on a voyage of exploration near the end of the tenth century A.D. When he arrived at Greenland with his ships and people, they set up settlements that flourished for several hundred years, and they were able to grow a variety of crops, including corn, that had never before been cultivated in Greenland. They were also able to raise their animals and, in general, enjoy a prosperous life. During the same warm period, Polynesian people in the Pacific, taking advantage of winds flowing throughout the Pacific, were able to sail to and colonize islands over vast areas of the Pacific, including Hawaii.[2]

While some prospered in Western Europe and the Pacific during the MWP, other cultures were not so fortunate. Associated with the warming period were long, persistent droughts (as long as human generations) that appear to have been partially responsible for the collapse of sophisticated cultures in North America and Central America. The collapses were not sudden but occurred over periods of

18.1 Global Change and Earth Systems Science: An Overview

Preston Cloud, a famous Earth scientist interested in the history of life on Earth, human impact on the environment, and the use of resources, proposed two central goals for Earth sciences:

1. Understand how Earth works and how it has evolved from a landscape of barren rock to the complex landscape dominated by the life we see today
2. Apply that understanding to better manage our environment

Cloud's goals emphasize that our planet is characterized by a complex evolutionary history. Interactions between the atmosphere, the oceans, solid Earth, and the biosphere (**Figure 18.1**, page 620) have resulted in the development of a complex and abundant diversity of landforms—continents, ocean

many decades, and, in some cases, the people just moved away. These included the people living near Mono Lake on the eastern side of the Sierra Nevada in California, the Chacoan People in what is today Chaco Canyon in New Mexico in the southwestern United States, and the Maya civilization in the Yucatan of southern Mexico and Central America.

Today, we are worried about present warming trends. If they continue and accelerate or increase, we may again face a prolonged drought in the southwestern United States, as well as in other parts of the world, which may wreak havoc on the ability to produce the food that the 7 billion people upon Earth require.[2]

When the MWP ended, it was followed by the Little Ice Age (LIA), which lasted several hundred years, from mid-1400 to 1700 A.D. The cooling of the LIA made it more difficult for people in Southeast Asia and Western Europe. Angkor Wat, with its palace and temple in Cambodia, was constructed in 1181. The region flourished for several hundred years, as canals and reservoirs irrigated vast rice fields. The water supply from summer monsoon rains was reliable, and people prospered. With climate change and the transition to the LIA, monsoon rains weakened, and water became scarce. The Angkorian civilization was in decline by the fifteenth century and collapsed by the end of the sixteenth century. The collapse was gradual, and people left the city, moving to smaller communities. Why the collapse occurred is not fully understood, but it was in part due to the onset of the LIA and a more volatile climate, with reduced monsoon rains and drought. In short, the food supply diminished as water resources became scarce.[2] During the LIA, storms, wet periods, extremes of heat and cold, and climate change caused a number of problems. Some winters were very cold, and, during the very cold winter of 1683–1684, the River Thames in London was frozen solid for 2 months, and sea ice extended for kilometers into the North Sea, closing harbors and significantly restricting shipping. Crop failures occurred in Western Europe during the LIA, and the population was devastated by the Black Plague that reached out into the Atlantic and Iceland by about A.D. 1400. With the cooling times, increasing sea ice, and more environmental stress, trade with Greenland was restricted. Eventually, the colonies in North America and Greenland were mostly abandoned. Part of the reason for the abandonment in North America and, particularly, in Newfoundland, was that the Vikings may not have been able to adapt to the changing conditions, as did the Inuit peoples living there. As times became tough, the two cultures collided, and the Vikings, despite their fierce reputation, were not as able to adapt to the changing, cooler times as were the Inuit.

We do not know what caused the MWP, and the details about it are somewhat obscured by the lack of sufficient climate data during that period with which to estimate temperatures. We do know that it was warm in Western Europe and the North Atlantic, and we can't blame that on the burning of fossil fuels. What this may suggest is that more than one factor may cause warming; the present warming, for the most part, is clearly the result of the emissions of carbon dioxide into the atmosphere from burning fossil fuels and land use changes. Perhaps a lesson for us is that changes in the most recent past warming (MWP) had winners and losers. Today, the world population is 7 billion, and half of us live in cities. The world population during the MWP was about 500 million, and agriculture was blooming. However, persistent droughts during the MWP apparently caused pain and suffering over much of the semiarid areas of the world, from coastal California to the southwestern United States, as well as Central and South America. This is a red flag! The potential effects of prolonged, persistent drought and loss of food production for the world, if present warming continues, is a serious threat, and we will explore this, along with other aspects of present warming trends, throughout this chapter.

basins, mountains, lakes, plains, and slopes—as well as the abundant and diverse life-forms that inhabit a broad spectrum of habitats.

Until recently, it was thought that human activity caused only local or, at most, regional environmental change. It is now generally recognized that the effects of human activity on Earth are so extensive that we are actually involved in an unplanned planetary experiment. To recognize and perhaps modify the changes we have initiated, we need to understand how the entire Earth works as a system. The discipline, called **Earth systems science**, seeks to further this understanding by learning how the various components of the system—the atmosphere, oceans, land, and biosphere—are linked on a global scale and interact to affect life on Earth.[4] In the following sections, we'll look at some tools for studying change.

The Geologic Record

Sediments deposited on floodplains or in lakes, bogs, glaciers, or the ocean may be compared to the

FIGURE 18.1 Earth from space The blue of the oceans, the land and biosphere of Africa, and the dynamic clouds of the atmosphere, all interacting in the Earth system. *(Johnson Space Center/NASA)*

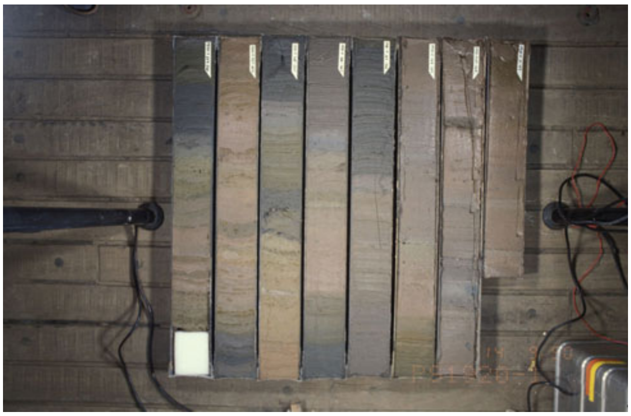


FIGURE 18.2 Examining cores Marine core from seafloor under the Antarctic Ice Shelf is being examined. *(Hannes Grobe/Alfred Wagner Institute for Polar and Marine Research)*

pages of a history book. Organic material that is often deposited with sediment may be dated by using a variety of methods to provide a chronology. In addition, the organic material can tell a story concerning the past climate, life-forms in the area, and environmental changes that have taken place. Ocean sediments are sampled by drilling from a ship or on an ice shelf and extracting a core several centimeters in diameter that may be a few hundred meters to over 1,000 m long (**Figure 18.2**). On land, sediment may be sampled by drilling or trenching or from a natural exposure.

FIGURE 18.3 Ice core Collecting an ice core in 2005 on the Greenland Ice Cap for examination of the climate record it contains. *(Alfred Wagner Institute for Polar and Marine Research)*

One of the most significant uses of the geologic record has been the examination of glacial ice. Glacial ice contains trapped air bubbles that may be analyzed to provide information concerning atmospheric carbon dioxide (CO_2) and methane (CH_4) concentrations when the ice formed. These trapped air bubbles are atmospheric time capsules from the past and have been used to analyze the carbon dioxide content of air as old as 800,000 years.[5] The method of studying the glacial record is to drill the ice and extract an ice core, which can be sampled (**Figure 18.3**).[6] Glaciers also contain a record of heavy metals, such as lead, that settle out of the atmosphere, as well as a variety of other chemicals that can be used to study recent Earth history.

The geologic record is the primary source of data and evidence for understanding Earth's history and changing environment. Without ice cores and layered sediment, we would know little about long-term change or be able to put the change in the context of what is changing today.

Real-Time Monitoring

Monitoring is the regular collection of data for a specific purpose; real-time monitoring refers to collecting these data while a process is actually occurring. For example, we often monitor the flow of water in rivers to evaluate water resources or flood hazard. In a similar way, samples of atmospheric gases can help establish trends or changes in the composition of

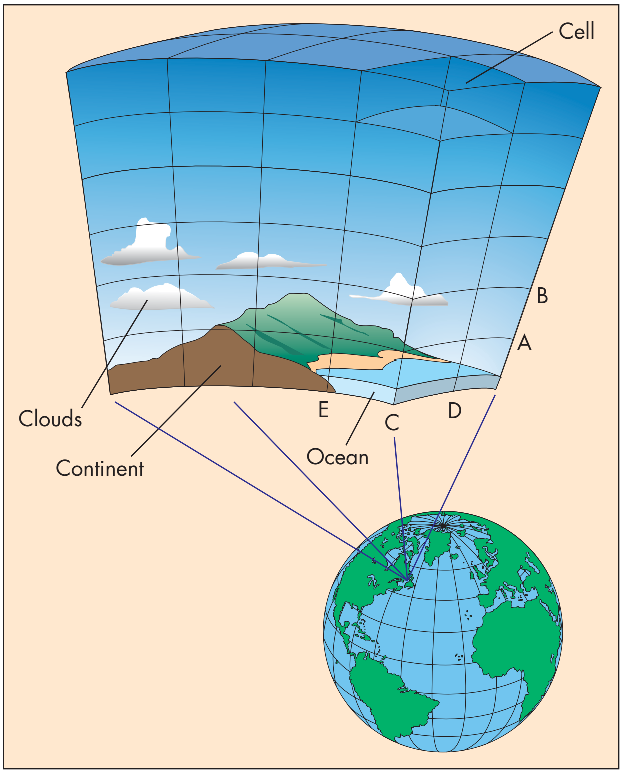
the atmosphere; measurements of temperature and the composition of the ocean are also used to examine changes within them. Gathering of real-time data is necessary for testing models and for calibrating the extended prehistoric record derived from geologic data.

Methods of monitoring vary with the subject being measured. For example, the impacts from mining may be monitored by evaluating remotely sensed data collected by using satellite or high-altitude aerial photographs. However, the most reliable data are often derived from ground measurements that establish the validity of the airborne or satellite measurements.

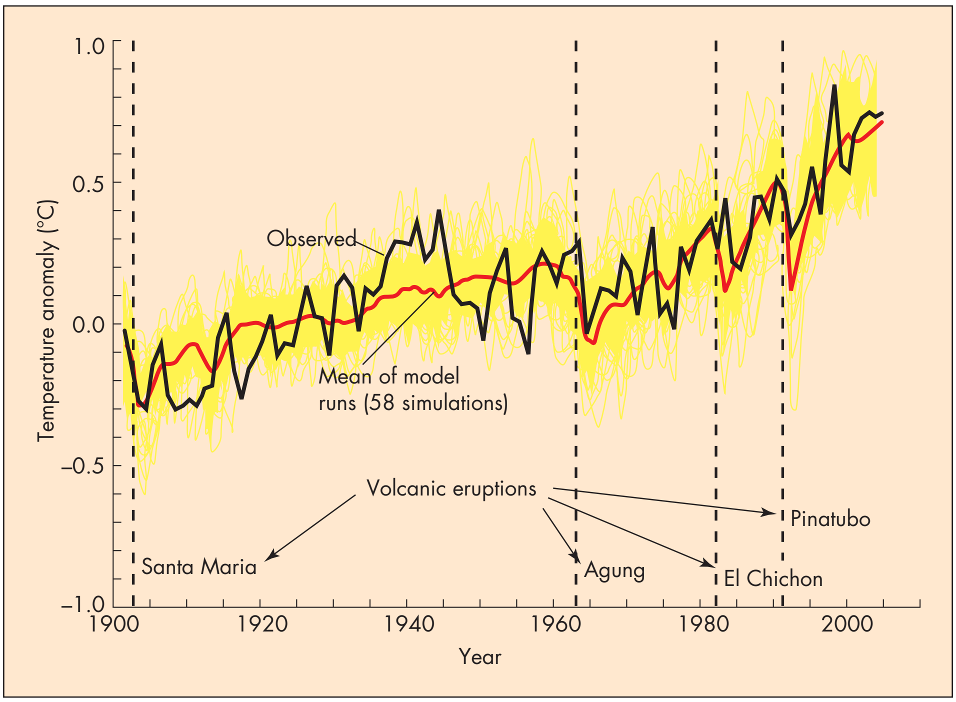
Mathematical Models

Mathematical models use numerical means to represent real-world phenomena and the linkages and interactions between the processes involved. Mathematical models have been developed to predict the flow of surface water and groundwater, erosion and deposition of sediment in river systems, ocean circulation, and atmospheric circulation.

The global change models that have gained the most attention are the climate models. These models predict changes in climate on a global scale.[7] Data used in the calculations are arranged into large cells that represent several degrees of latitude and longitude; a cell typically represents an area about the size of Oregon (Figure 18.4). In addition, there are usually 6 to 20 levels of vertical cells representing the lower



(a)



(b)

FIGURE 18.4 Modeling climate (a) Idealized diagram illustrating the cells used in climate models. (b) Observed (black) and predicted temperature changes 1900–2005. The predicted mean (red line) is the average of 58 different simulations using 14 different climate models. The yellow is the variability in simulations. *(IPCC. 2007. The Physical Science Basis: Working Group I. Contribution to the Fourth Assessment Report. New York: Cambridge University Press)*

atmosphere. Calculations involving equations for major atmospheric processes are then used to make predictions.

There is growing confidence that climate models provide believable quantitative estimates of known past and predicted future climate change.[7] An example of observed versus predicted change is shown in Figure 18.4b. The models are based on physical principles (e.g., conservation of energy and mass) that are used to produce a mathematical representation of **Earth's climate system**, defined as the system consisting of the atmosphere, hydrosphere, land surface, biosphere, and cryosphere (i.e., ice, snow, and frozen ground), which are linked and often interact with each other in complex ways. Before discussing climate change further, we need a basic understanding of Earth's climate and atmosphere.

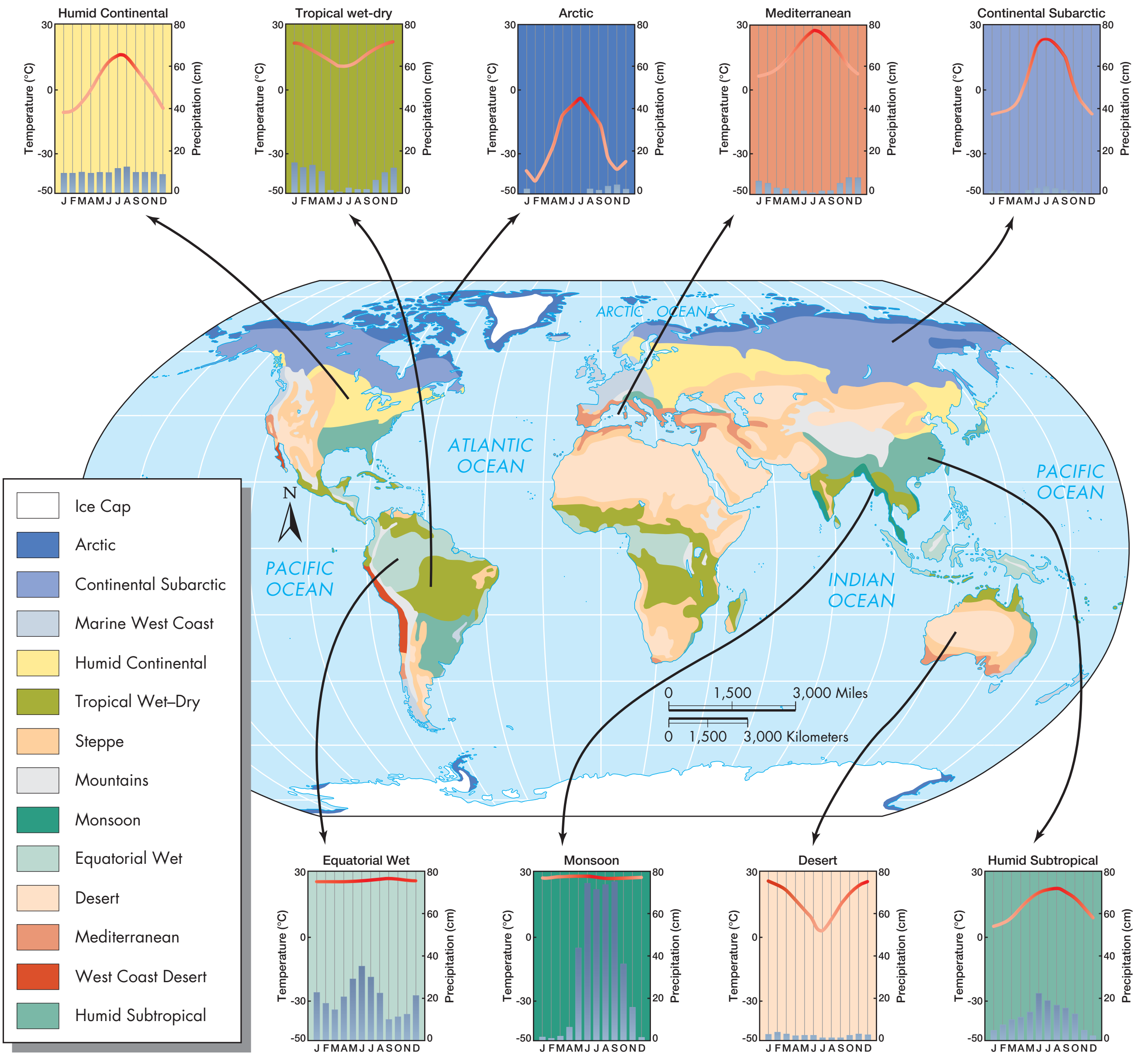
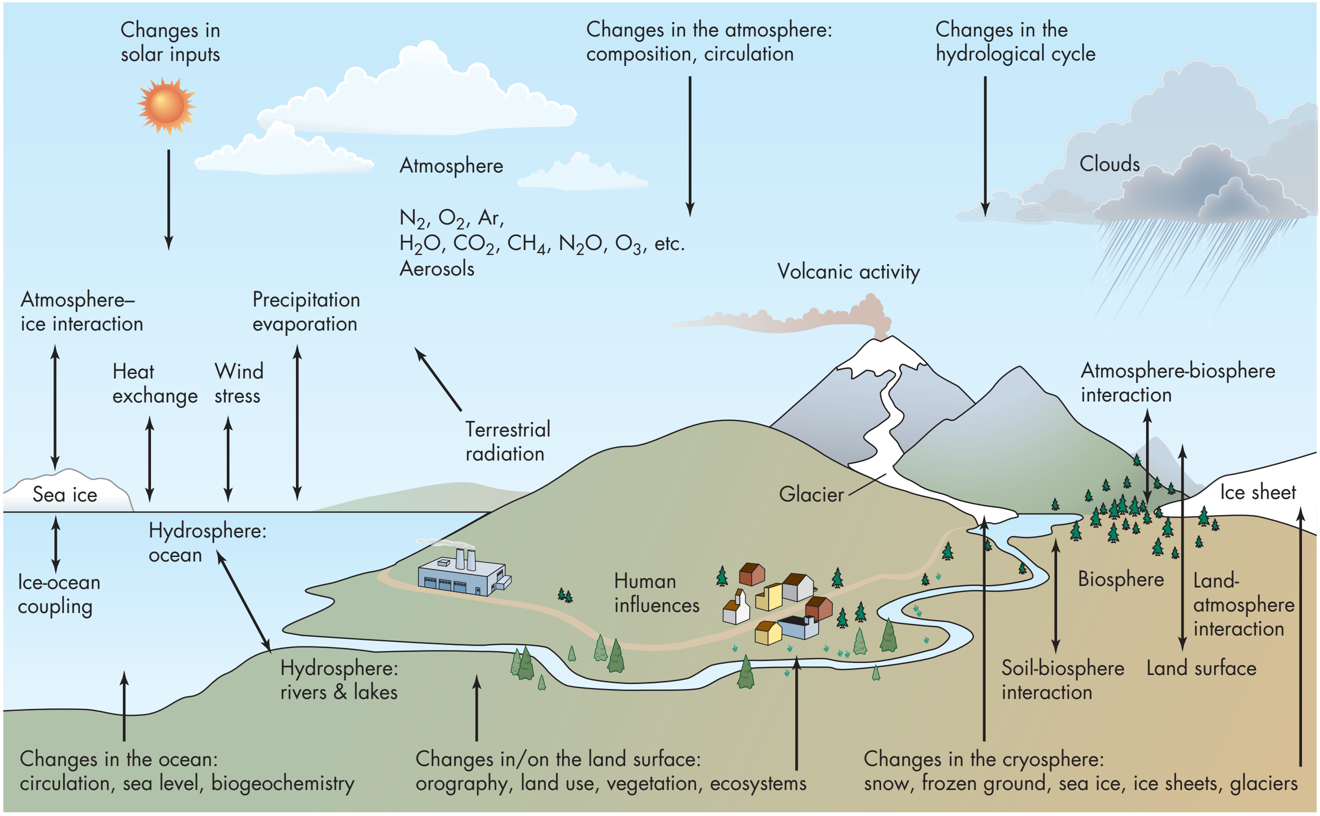


FIGURE 18.5 Climates of the world (a) Characteristic temperature and precipitation conditions. Temperature is represented by the red line, and precipitation is shown as bars. *(Modified after Marsh, W. M., and Dozier, J.* Landscapes: An Introduction to Physical Geography. *Copyright © 1981. John Wiley & Sons)* (b) Idealized diagram showing the complex, linked components and changes of the climate system that produce, maintain, and change the climates of the world. *(IPCC. 2007.* The Physical Science Basis: Working Group I. Contribution to the Fourth Assessment Report. *New York: Cambridge University Press)*



(b)

FIGURE 18.5 Continued

18.2 Earth's Climate and Atmosphere

We define **climate** as the characteristic atmospheric conditions—that is, the *weather*—at a particular place or region over time periods from seasons to years to decades. The climate at a particular location may be complex and consist of more than average precipitation and temperature. For example, it may be dependent on infrequent or extreme seasonal patterns, such as rain in the monsoon season of parts of India. The major climatic zones on Earth are shown in **Figure 18.5a**. Selected processes and changes that produce and maintain the climate system are shown in **Figure 18.5b**.

Global circulation and movement of air masses in the atmosphere (**Figure 18.6**) produce the major climatic zones. Warm tropical air near the equator rises and moves north and south, descending in the midlatitudes (sometimes producing deserts). The air then rises again at higher latitudes and descends at the poles. There are three cells of circulation (called Hadley cells, named after George Hadley, who first described them) in each hemisphere. Simplified, warm air rises at the equator and moves toward the poles, where it sinks after going through cell 2 (see Figure 18.6), and return flow is along the surface toward the equator.

The lower, active part of the atmosphere, where weather occurs, is the troposphere. The structure of the atmosphere is shown in **Figure 18.7** (page 625). Air temperature and concentration of oxygen decrease with altitude in the troposphere. At the top of the troposphere, at an altitude that varies from about 18 km at the tropics to 7 km at the poles, it is very cold, and the temperature remains nearly constant for a few kilometers through the tropopause. The constant temperature with little air movement places a lid on the active lower atmosphere (i.e., troposphere). Temperature then increases in the stratosphere, only to decline again in the mesosphere. Nearly all (99 percent) of the

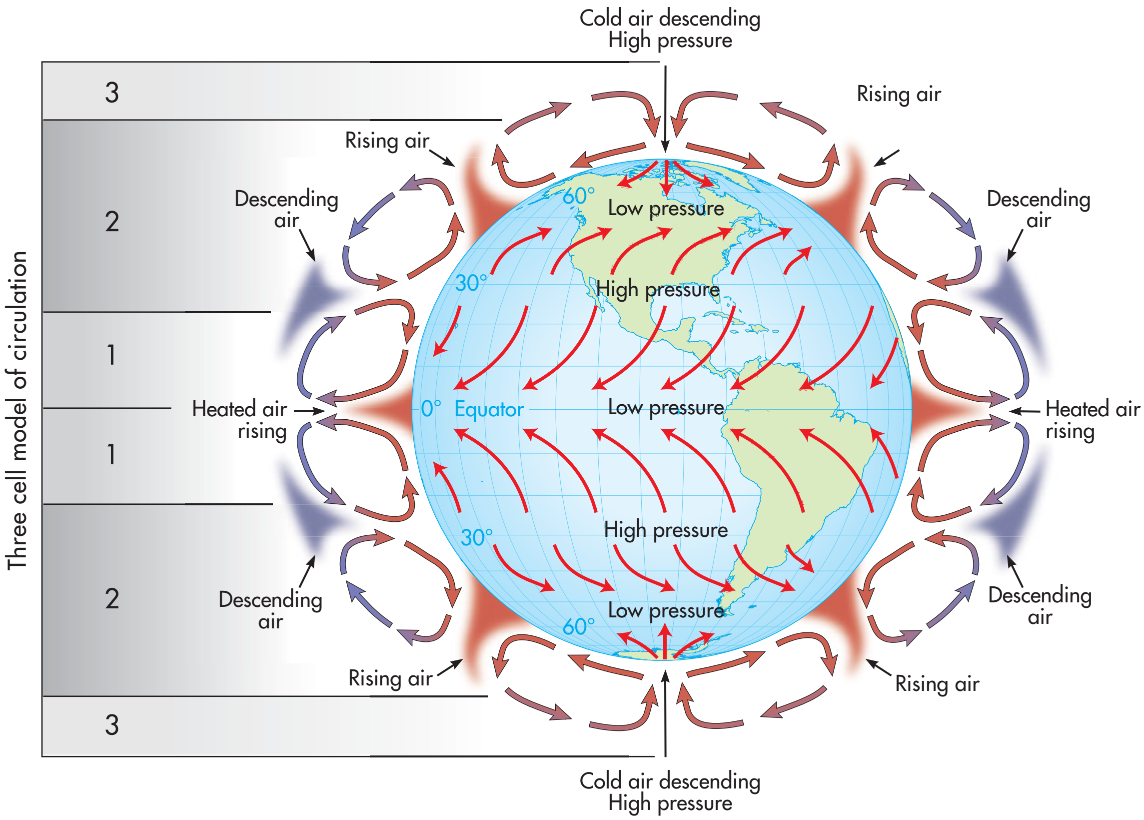


FIGURE 18.6 Atmospheric circulation Global circulation of the lower atmosphere, showing zones of rising and descending air masses. Heating of Earth's surface is uneven, producing differences in air pressure because cool air is denser than warm air. Warm air rises at the equator, and cool air sinks at the poles. As Earth rotates, three cells of circulating air (called Hadley cells, after George Hadley, who first proposed them) form in each hemisphere.

atmosphere by weight is below an altitude of about 30 km (20 mi).

The Atmosphere

Our atmosphere can be thought of as a complex chemical factory with many little-understood reactions taking place within it. Many of the reactions that take place are strongly influenced by both sunlight and the compounds produced by life. The air we breathe is (by volume) a mixture of nitrogen (N_2) (78 percent), oxygen (O_2) (21 percent), argon (Ar) (0.9 percent), carbon dioxide (CO_2) (0.03 percent), and other trace elements (less than 0.07 percent). It also contains compounds such as methane, ozone, carbon monoxide, oxides of nitrogen and sulfur, hydrogen sulfide, hydrocarbons, and various particulates, many of which are common air pollutants. The most variable part of the atmosphere's composition is water vapor (H_2O), which can range from approximately 0 percent to 4 percent by volume in the lower atmosphere.

With this brief introduction to the atmosphere and climate, we will now introduce the greenhouse effect (which is an atmospheric effect) followed by discussion of how we study past climate and human-induced global warming in terms of the history and process of global temperature change.

18.3 The Greenhouse Effect

For the most part, the temperature of Earth is determined by three factors: the amount of sunlight Earth receives, the amount of sunlight Earth reflects (and, therefore, does not absorb), and atmospheric retention of reradiated heat.[7] **Figure 18.8** (page 626) shows the basics of Earth's energy balance, which represents the equilibrium between incoming and outgoing energy.

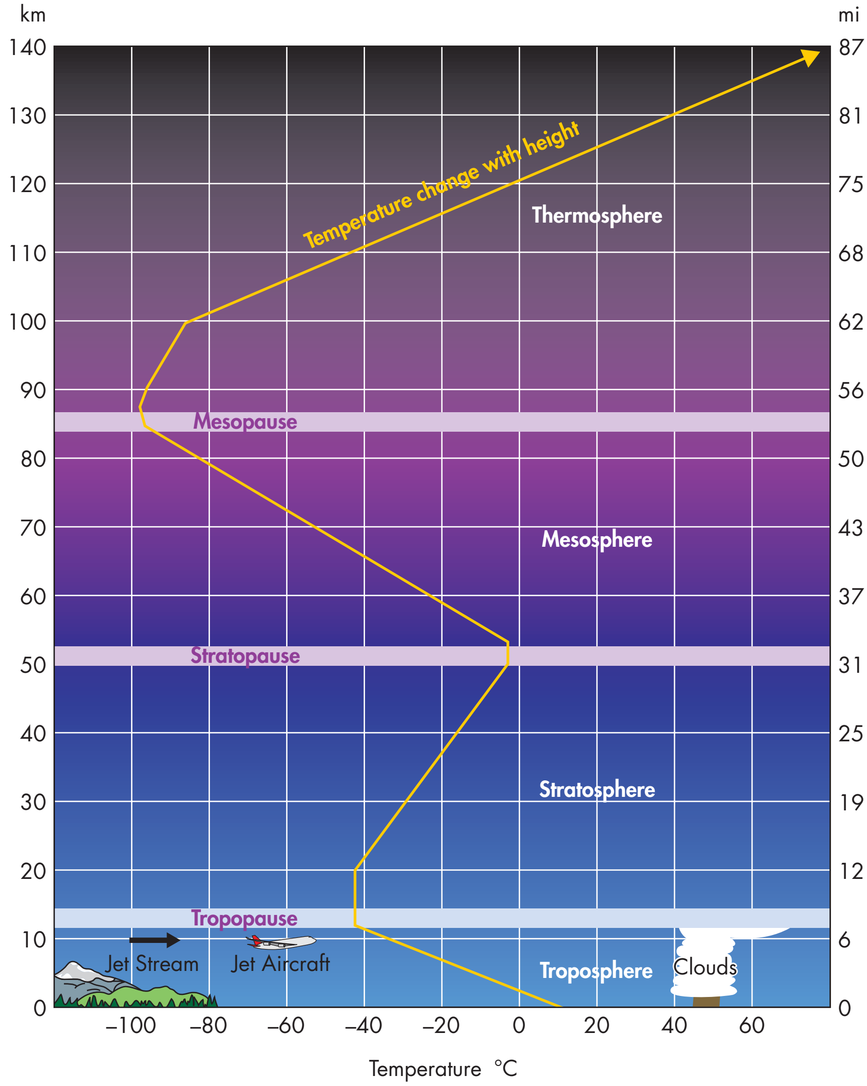


FIGURE 18.7 Structure of the atmosphere Atmospheric layers and temperature profile. The weather occurs in the troposphere below about 11 km but varies from 7 km at the poles to 18 km in the tropics. *(NOAA)*

Earth's energy balance today is slightly out of equilibrium, with about 1 W/m^2 more energy coming from the Sun than is lost to space. The energy we are talking about, W/m^2, is energy per unit time (joules/sec) per unit area (m^2). The units /m^2 represent power per unit area, but we speak of it as solar energy. The units/m^2 are widely used in global warming and climate change research.[6–8,]

Earth receives energy from the Sun in the form of electromagnetic radiation. The various types of electromagnetic energy are shown in **Figure 18.9** (page 627). Radiation from the Sun is relatively short wave and mostly visible, whereas Earth radiates relatively long-wave infrared radiation (**Figure 18.10**, page 628). The hotter an object, whether it is the Sun, Earth, a rock, or a lake, the more electromagnetic energy it emits. The Sun, with a surface temperature of 5,526°C (10,472°F), radiates much more energy per unit area than does Earth, which has an average near surface temperature of 15°C (59°F).

Absorbed solar energy warms Earth's atmosphere and surface, which then reradiate the energy back into space as infrared radiation.[7] Water vapor and several other atmospheric gases—including carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbons

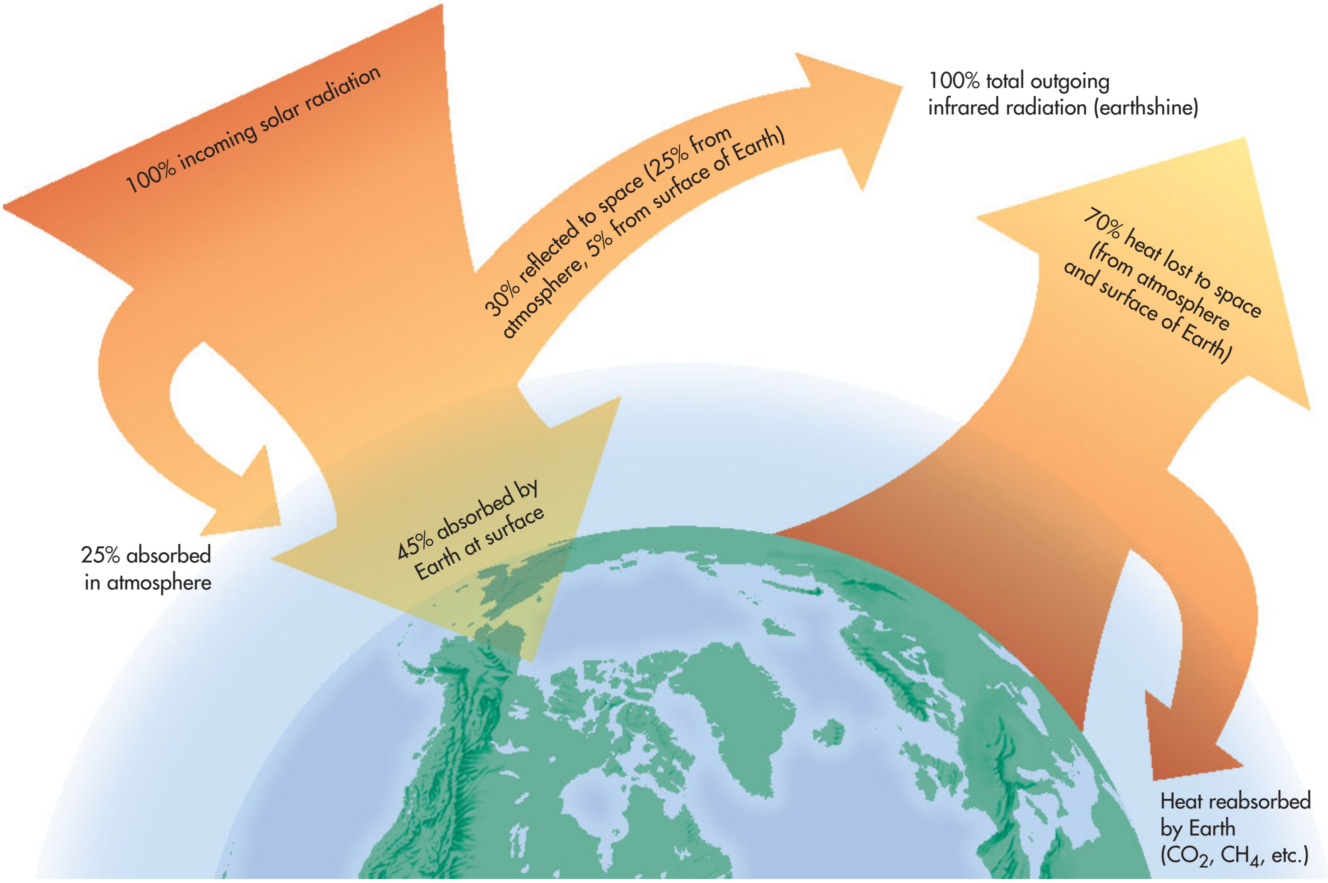


FIGURE 18.8 Annual energy flow to Earth from the Sun The relatively small component of heat from Earth's interior to the near-surface environment is shown. Over the past 50 years, incoming solar energy per unit time per unit area (W/m^2) has exceeded outgoing solar energy by about 1 W/m^2. *(Modified after Pruitt, N. L., Underwood, L. S., and Surver, W. 1999.* BioInquiry, Learning System 1.0, Making Connections in Biology. *Hoboken, NJ: John Wiley & Sons; and Hansen, J. 2004. Defusing the global warming time bomb.* Scientific American *290(3):68–77)*

(CFCs) (i.e., human-made chemicals used in air conditioners and refrigerators)—tend to trap heat. That is, they absorb some of the energy radiating from Earth's surface and are thereby warmed. As a result, the lower atmosphere of Earth is about 40°C warmer than it would be if all of its radiation escaped into space without this intermediate absorption and warming. This effect is somewhat analogous to the trapping of heat by a greenhouse and is therefore referred to as the **greenhouse effect** (Figure 18.11, page 628).

It is important to understand that the greenhouse effect is a natural phenomenon that has been occurring for millions of years on Earth, as well as on other planets in our solar system. Without heat trapped in the atmosphere, Earth would be much colder than it is now, and all surface water would be frozen. Most of the natural "greenhouse warming" is due to water vapor and small particles of water in the atmosphere. However, potential global warming due to human activity is related to carbon dioxide, methane, nitrogen oxides, and chlorofluorocarbons. In recent years, the atmospheric concentrations of these gases and others have been increasing because of human activities. These gases tend to absorb infrared radiation from Earth, and it has been hypothesized that Earth is warming because of the increases in the amounts of these so-called greenhouse gases. With our understanding of Earth system science, climate, and atmospheric processes, we are ready to discuss how we study climate change.

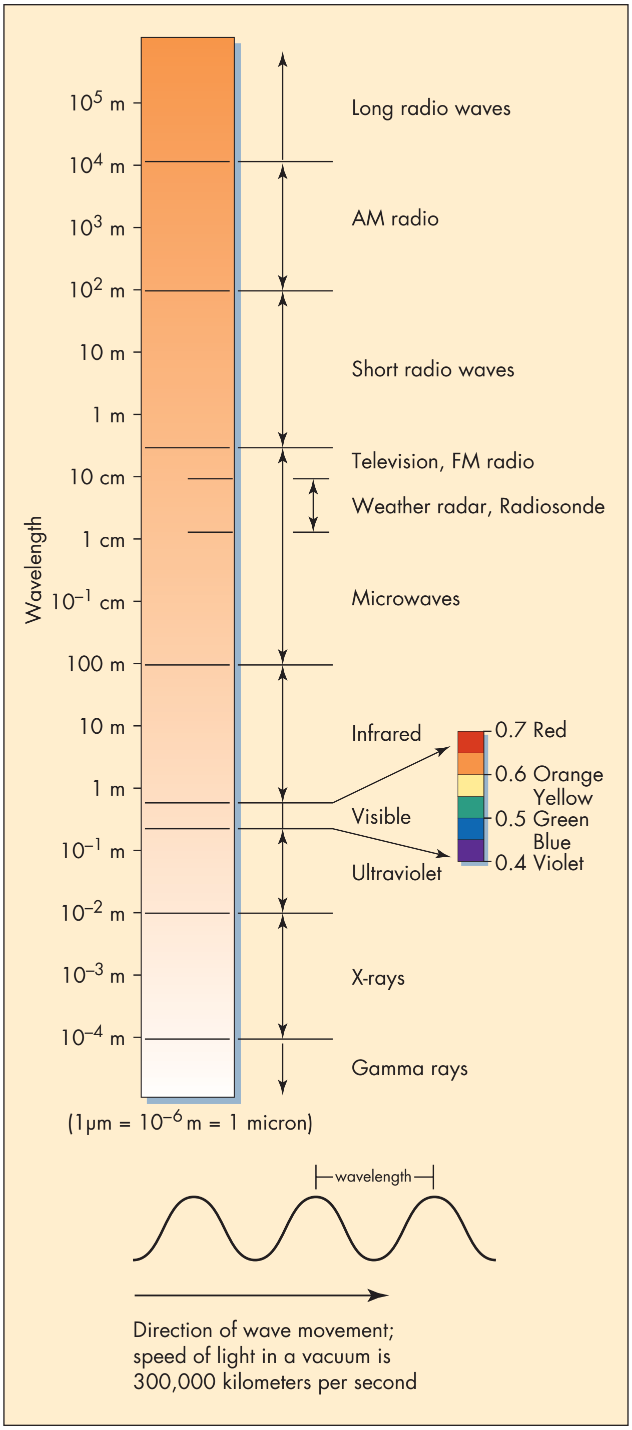


FIGURE 18.9 The electromagnetic spectrum The range in wavelength, distance between one wave crest to the next, is enormous, from millionths of a meter for X-rays and gamma rays to hundreds of thousands of meters for long radio waves. In a vacuum waves travel at the speed of light—300,000 km (186,411 mi) per second.

18.4 How We Study Past Climate Change

The data gathered to document and better understand climate change are from a variety of time scales and over variable regions—from continents, to the oceans, to hemispheres, and to the entire planet. There are three main time periods for which data are available:[9]

- **The instrumental record.** Starting about 1860, measurements of temperatures have been made at various locations on land and in the oceans. This is the data shown in Figure 18.12 (page 629). The earliest records are from the late seventeenth and early eighteenth centuries, and the network of stations has significantly increased over time. About 1,000 individual, but variable, records exist from the late nineteenth century. Today, temperature is measured (monitored at short time intervals) at about 7,000 stations around the world. The concentration of carbon dioxide in the atmosphere has been measured since about 1960. Accurate measurements of the production of solar energy have been taken over the past several decades.

- **The historical record.** A variety of historical records go back several hundred years. Included are people's written recollections (e.g., books, newspapers, journal articles, personal journals) of the Medieval Warm Period and the Little Ice Age, as well as ships' logs, travelers' diaries, and farmers' crop records. These are not generally quantitative data, but they contain qualitative information about the climate of the past.

- **The paleo-proxy record.** The instrumental record is short, and most of the historical information is not quantitative. As a result, there has been a need for extending the record back further. Paleoclimatology (i.e., the study of past climate) is part of Earth science. It is clear that the paleo record of Earth climate has provided some of the strongest data to support and test theories of recent climate change. The term **proxy data** refers to data that are not strictly climatic but that can be correlated with climate, such as temperature of the land or sea. Some of the information gathered as proxy

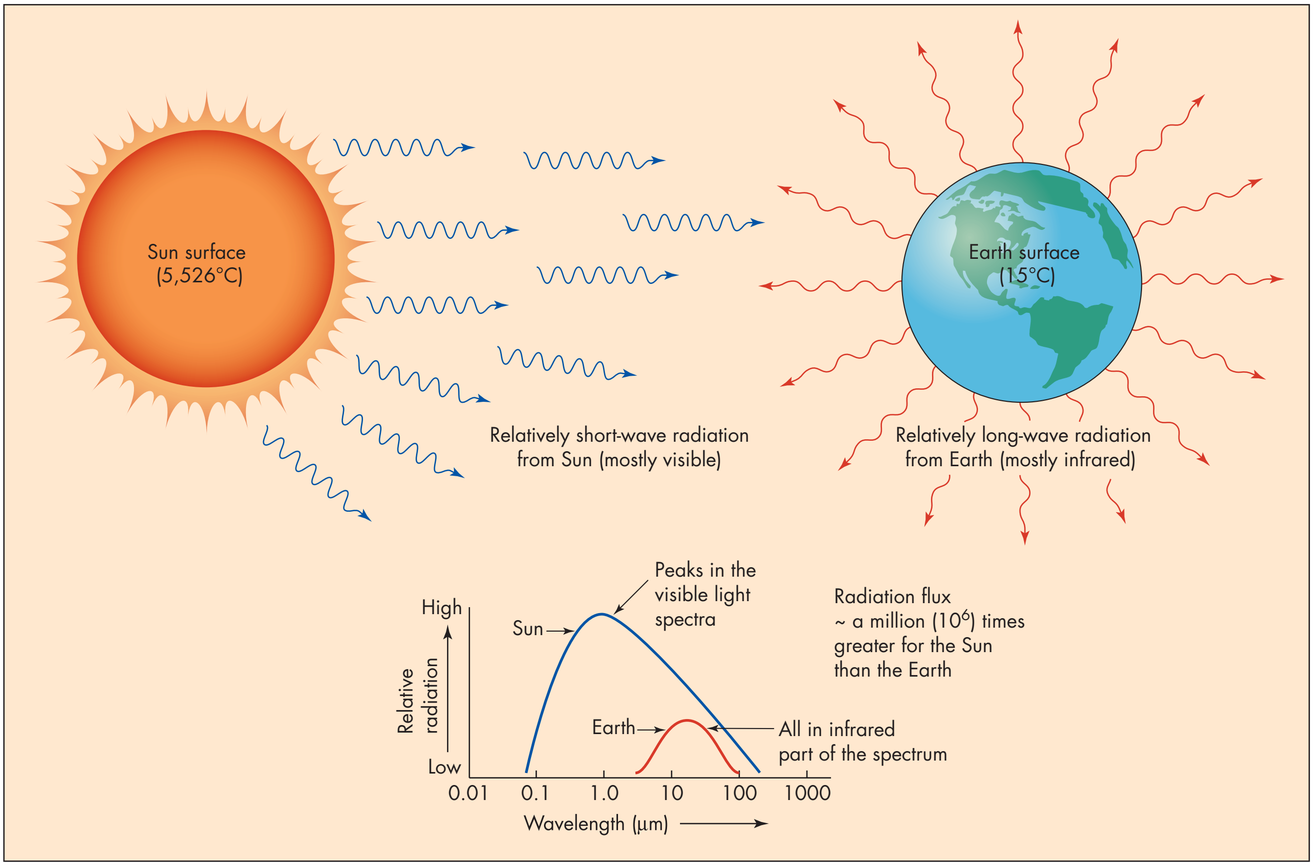


FIGURE 18.10 Earth–Sun Idealized diagram comparing the emission of energy from the Sun with that from Earth. Notice that the solar emissions have a relatively short wavelength, whereas those from Earth have a relatively long wavelength. *(Modified after Marsh, W. M., and Dozier, J.* Landscapes: An Introduction to Physical Geography. *Copyright © 1981. John Wiley & Sons)*

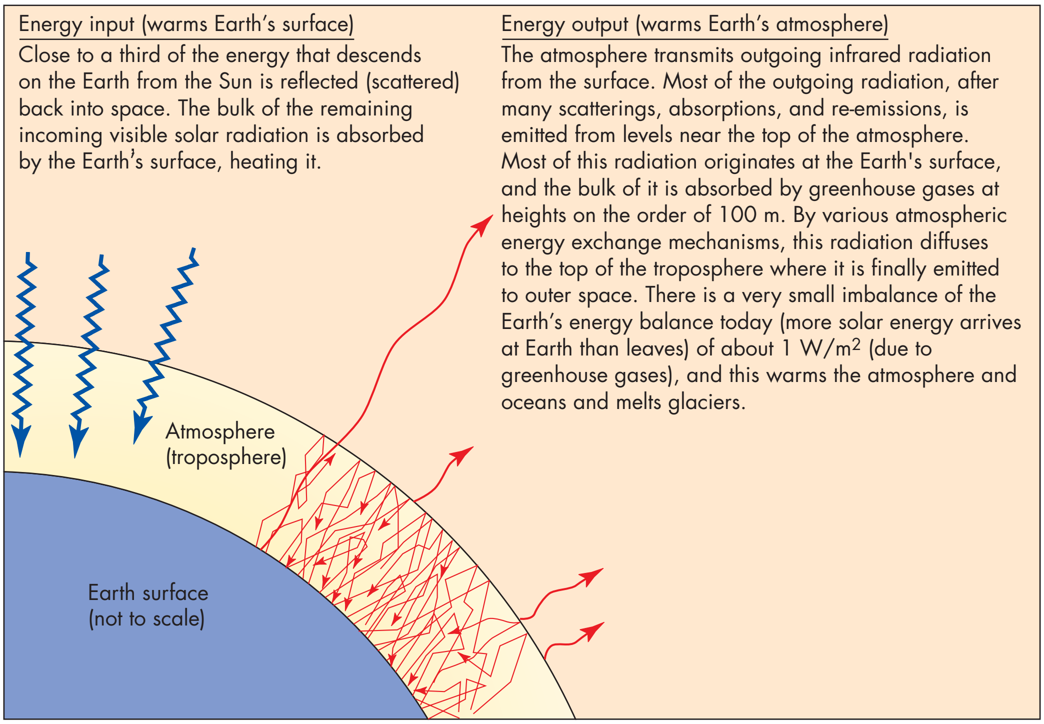


FIGURE 18.11 Greenhouse effect Idealized diagram showing the greenhouse effect. Incoming visible solar radiation (sunshine) is absorbed by Earth's surface, warming it. Infrared radiation is then emitted at the surface of Earth as earthshine to the atmosphere and outer space. Most of the infrared radiation emitted from Earth is absorbed by the atmosphere, heating it and maintaining the greenhouse effect. *(Developed by M. S. Manalis and E. A. Keller, 1990)*

data includes natural records of climate variability, as indicated by tree rings, ocean sediments, ice cores, fossil pollen, corals, and carbon-14 (^{14}C).The disadvantages of paleo-proxy data is obvious: The data are not direct measurements of temperature but must be inferred. In spite of this, the paleo-proxy record of change from the geologic record provides the best direct record of change before the historical and instrumental periods.

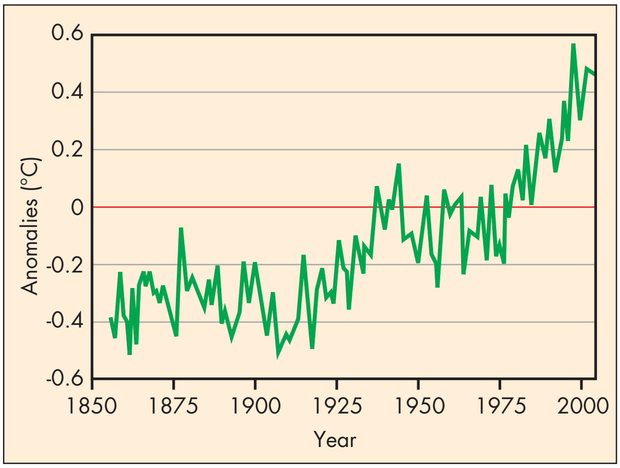


FIGURE 18.12 Temperature change Change in temperature from about 1830 to 2005, with departure from the average temperature from 1960 to 1990. In recent years, the anomaly has been about 0.5 to 0.6°C from the 1960–1990 average (shown as 0 on the graph). *(Source: NOAA. www.ncdc.noaa.gov)*

We have previously discussed (in Section 18.2) sediment cores and ice cores, and we will now consider other paleo-proxy data: tree rings, pollen, corals, carbon-14, carbon dioxide, and methane.

Tree Rings. The growth of trees is influenced by climatic conditions, such as the amount and variability of rainfall. Most trees put on one growth ring per year, and the width and density and isotopic composition of annual rings provides information about the variability of the past climate. Tree ring chronology, known as *dendrochronology*, has produced a proxy record of climate that extends back over 10,000 years (**Figure 18.13**).

Pollen. Pollen (from flowers, trees, and other plants), along with other sediment, accumulates in a variety of environments, including oceans, bogs, and lakes. Scientists study the abundance and types of pollen in order to investigate past climate. For example, if the climate cools, there will be a change in the assemblage of pollen in sediments that reflects the change in climate. If pollen is found in sufficient quantity, it may be dated, and, since the grains are preserved in sedimentary layers that also might be

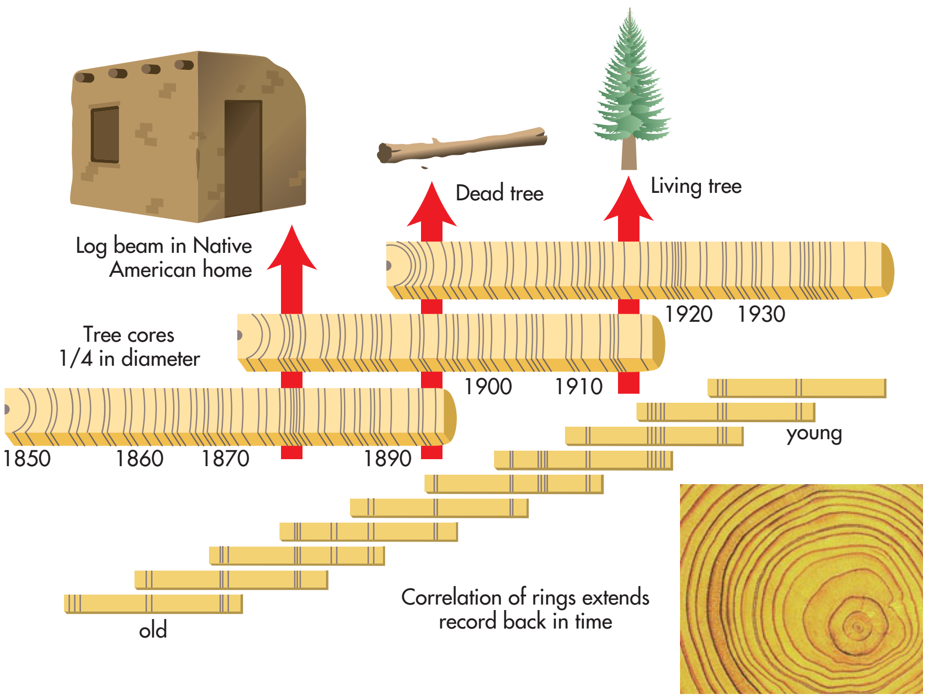


FIGURE 18.13 Tree ring chronology Dendrochronology provides proxy climate information, such as relative rainfall or periods of drought and carbon-14 activity, which is an indicator of solar variability. *(Modified from NOAA. 2010. www.ncdc.noaa.gov)*

dated, a chronology can be developed. Based on the types of plants found at different times, the climatic history can be reconstructed.

Corals. Coral reefs consists of corals (and other organisms) that have hard skeletons composed of calcium carbonate ($CaCO_3$) extracted by the corals from the seawater. The calcium carbonate contains isotopes of oxygen, as well as a variety of trace metals, that can be used to estimate the temperature of the water that the coral grew in. Thus, corals are a source of paleo-proxy data that can help us to interpret climate change. Corals may be dated by using several dating techniques, and a chronology of change over time may be constructed.

Carbon-14. The production of ^{14}C produced in the upper atmosphere is caused by collisions between neutrons and nitrogen-14 (^{14}N). The nitrogen is part of what are called *cosmic rays* that come from outer space and are a product of the energy from the sun. Solar activity can be observed from the frequency of sunspots, which are called *spots* because they are observed as dark areas on the sun, surrounded by lighter areas. As sunspot activity increases, the energy from the sun that reaches Earth also increases. The frequency of sunspots has been observed by people for about 1,000 years and accurately measured for decades. When sunspot activity is high, there is an associated solar wind, which produces ionized particles consisting predominately of protons and electrons, emanating from the sun. The solar wind reflects cosmic rays (including nitrogen-12, ^{12}N). As a result, the amount of ^{14}C is reduced. The record of ^{14}C in the atmosphere is correlated to tree ring chronology (discussed earlier). Each ring of wood of known age contains carbon, and the amount of ^{14}C can be measured. If the climatic record for a period of time is known, it may be correlated with ^{14}C. Thus, we can examine solar energy output, extending back thousands of years, by studying tree rings and the carbon-14 they contain. Based upon the ^{14}C record and its link to solar energy, it appears that the production of solar energy was slightly higher around A.D. 1000, during the Medieval Warm Period, and was slightly lower during the Little Ice Age from about A.D. 1400 to 1800. The effect of solar radiation on recent climate change (during the instrumental record) can account for a small percentage of observed changes in climate. The variability of solar energy is not sufficient to explain the warming since about 1960.

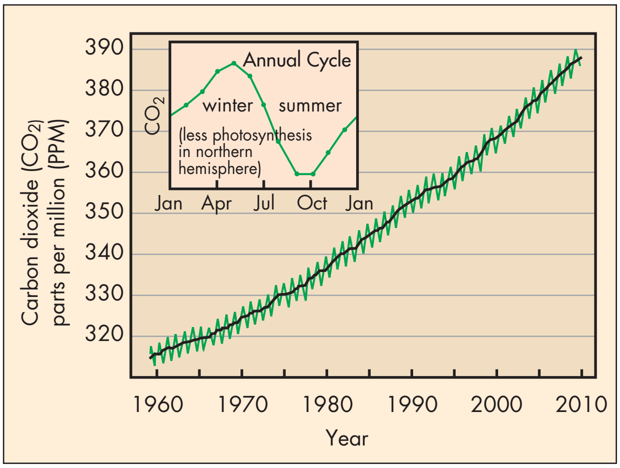


FIGURE 18.14 Atmospheric concentration of carbon dioxide at Mauna Loa, Hawaii *(Source data from Scripps Institute of Oceanography, NOAA, and C. D. Keeling, at www.esrl.noaa.gov/gmd/ccgg/trends/co₂_data_mlo.html)*

Carbon Dioxide. The concentration of global carbon dioxide in the atmosphere is a proxy for global temperature change; it is arguably the most important proxy in the study of past climate. There are carbon dioxide measurements from the instrumental record since about 1960 (**Figure 18.14**), and these have been extended back through the measurements from trapped air in glaciers to about 800,000 years ago (see **Figure 18.15**).[10]

Methane. The concentration of methane in the atmosphere is a proxy for global temperature change, arguably one of the most important proxies in the study of past climate. Methane measurements extend back about 800,000 years, with measurements from trapped air in glaciers (Figure 18.15).[10]

With a better understanding of atmospheric processes and how we can study past climate, we now turn to global warming, which is often considered one of our most significant environmental concerns.

18.5 Global Warming

Global warming is defined as the observed increase in the average temperature of the near-surface land and ocean environments of Earth. We are particularly interested in warming in the past

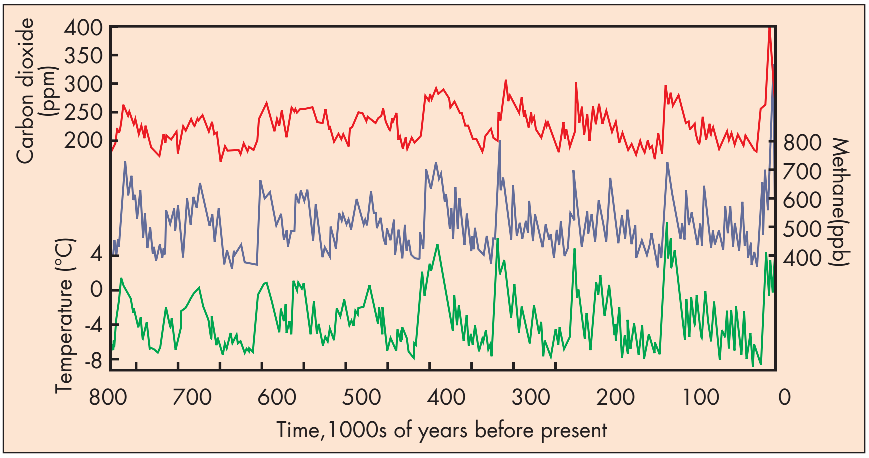


FIGURE 18.15 Carbon dioxide and methane in the atmosphere Average concentration of atmospheric carbon dioxide over the past 800,000 years, based on measurements of air bubbles trapped in glacial ice. *(Modified after Brook, E. 2008. Paleoclimate: Windows on the greenhouse.* Nature *453:291–292)*

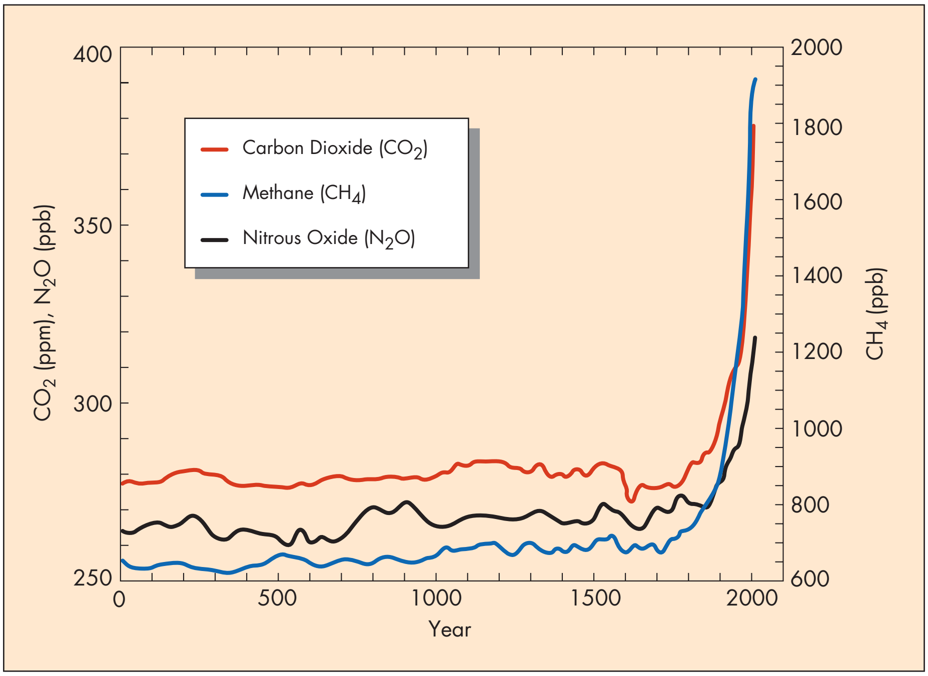


FIGURE 18.16 Concentrations of greenhouse gases in the past 2,000 years Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased rapidly in recent decades. *(Modified after IPCC. 2007.* The Physical Science Basis: Working Group I. Contribution to the Fourth Assessment Report. *New York: Cambridge University Press)*

100 years because a growing volume of evidence suggests that we are now in a period of global warming resulting from burning vast amounts of fossil fuels linked to the greenhouse effect. Does this mean we are experiencing human-induced global warming? Many scientists now believe that human processes in the past 100 years, as well as natural ones over geologic time, have contributed significantly to global warming.[6,7] We will begin our discussion by examining the link between the greenhouse effect and emissions of greenhouse gases.

Recent global warming is believed to be due in a large part to human emissions of greenhouse gases, such as carbon dioxide, methane, nitrogen oxides, and chlorofluorocarbons. **Figure 18.16** shows the increase in greenhouse gases over the past 2,000 years. Notice the very rapid rise in the past 100 years.

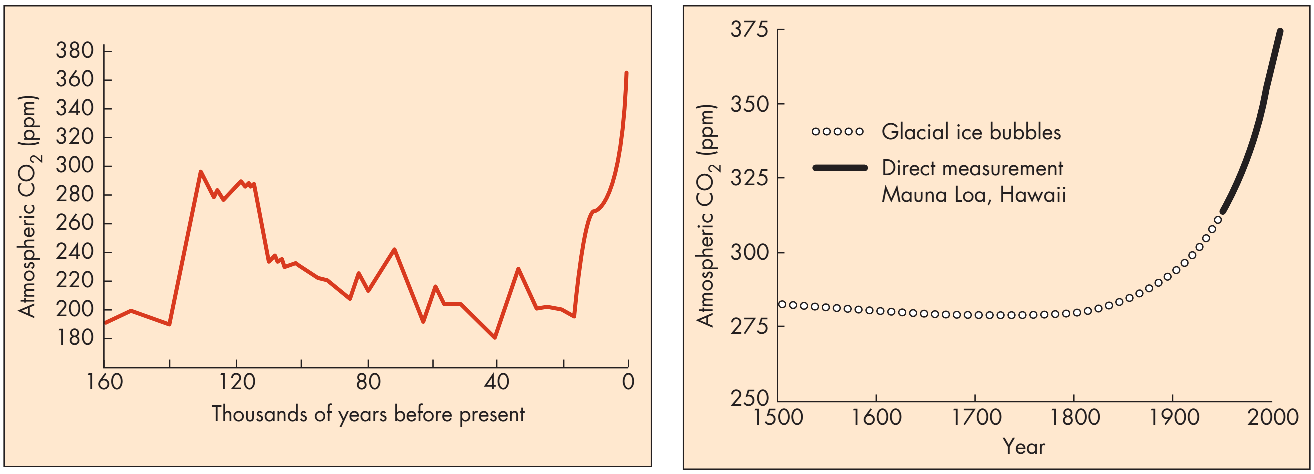
In recent years, the atmospheric concentrations of greenhouse gases and other gases that absorb infrared radiation from Earth or are transformed to others that do have been increasing. Since 1990, U.S. emissions of carbon dioxide have increased by

about 14 percent. Over the same period, U.S. emissions of methane decreased by about 7.5 percent, and nitrous oxide emissions decreased by about 4 percent. In 2008, the United States emitted about 7 billion metric tons of greenhouse gases. Of these, based on equivalent amount of the global warming potential (GWP), carbon dioxide accounted for 85.1 percent, methane 8.2 percent, nitrous oxide 4.6 percent, and chlorofluorocarbons 2.2 percent. The GWP is a weighted value where the warming potential of a greenhouse gas is compared as a ratio to that of carbon dioxide. Carbon dioxide is assigned a GWP of 1, methane is 21, and nitrous oxide 310. This means that molecule-by-molecule, methane is a more powerful greenhouse gas than carbon dioxide by a factor of 21 times. About 60 percent of the total human-caused (i.e., anthropogenic) greenhouse effect is from carbon dioxide because carbon dioxide accounts for the vast majority of total greenhouse gas emissions. World emissions of carbon dioxide in 2008 were about 30.4 billion metric tons, of which about 19 percent were from the United States.[11]

Measurements of carbon dioxide trapped in air bubbles of the Antarctic ice sheet suggest that, during most of the past 800,000 years, the atmospheric concentration of carbon dioxide has varied from a little less than 200 ppm to about 300 ppm.[7] The highest levels are recorded during major interglacial periods that occurred approximately 125,000 years ago and at the present (Figures 18.15 and **18.17**). Major interglacial periods have occurred about eight times during the past 800,000 years—about every 100,000 years. During each of these periods, the concentration of CO_2 in the atmosphere was similar to that of the most recent interglacial event, about 125,000 years ago.[12] At the beginning of the Industrial Revolution, the atmospheric concentration of carbon dioxide was approximately 280 ppm. Since 1860, fossil fuel burning has contributed to the exponential growth of the concentration of carbon dioxide in the atmosphere. The concentration of carbon dioxide in the atmosphere today exceeds 390 ppm, and it is predicted to reach at least 450 ppm—more than 1.5 times the preindustrial level—by 2050.

Global Temperature Change

The Pleistocene ice ages began approximately 2.6 million years ago, and, since then, there have been numerous changes in Earth's mean annual temperature. **Figure 18.18** shows the changes of approximately the past million years on several time scales. The first scale shows the entire million years (Figure 18.18a), during which there have been major climatic changes involving swings of several degrees Celsius in mean temperature. Low



(a) (b)

FIGURE 18.17 Carbon dioxide in the atmosphere (a) Concentration of atmospheric carbon dioxide for the past 160,000 years, based on evidence from Antarctica. *(Data in part from Schneider, S. H. 1989. The changing climate. Scientific American 261:74)* (b) Average concentration of atmospheric carbon dioxide from 1500 to 2000. *(Data in part from Post, W. M., et al. 1990. The global carbon cycle.* American Scientist *78(4):210–226)*

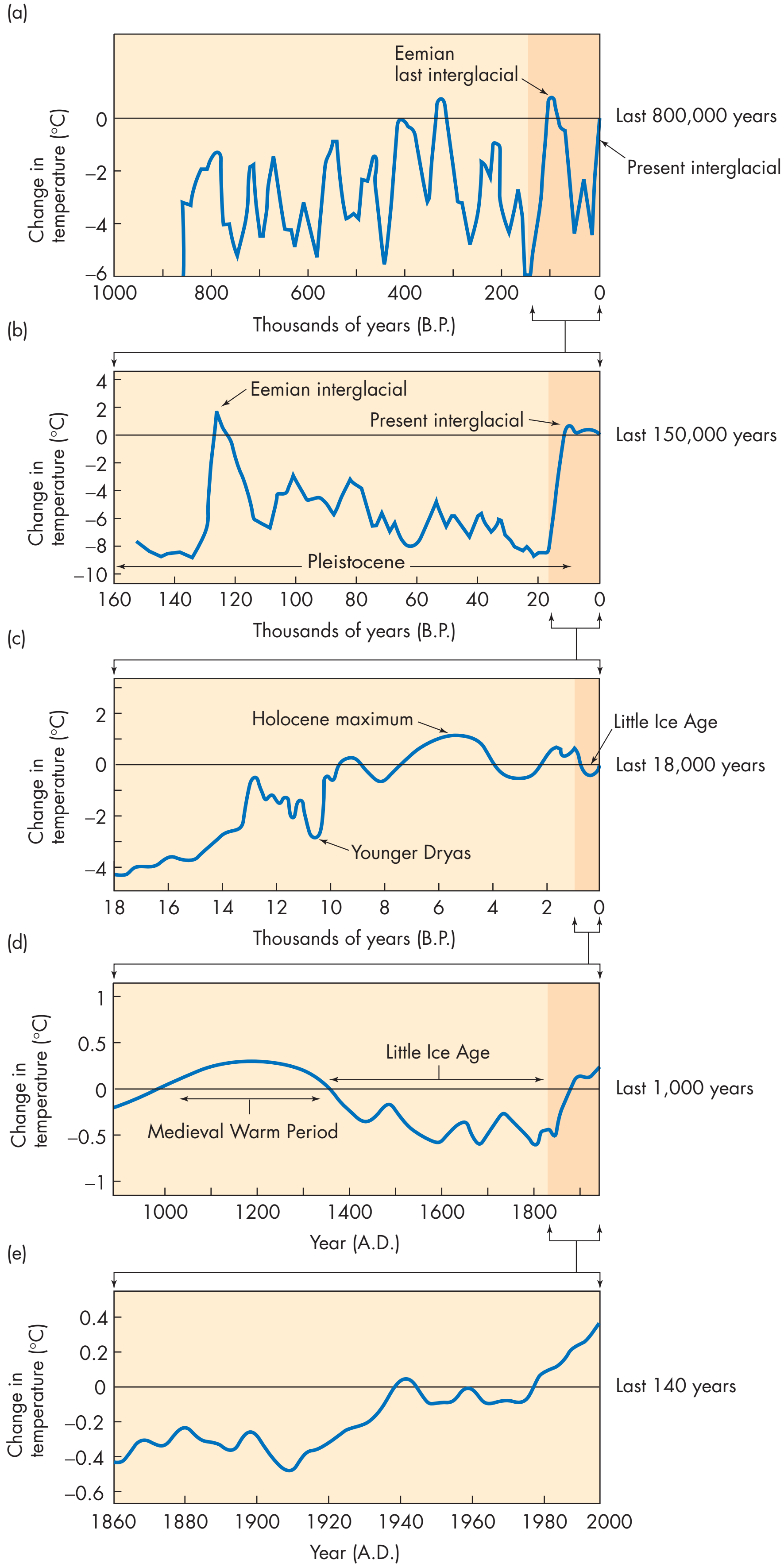


FIGURE 18.18 Changes in global temperature Change in temperature over different periods of time during the past million years. (a). The major peaks in temperature on (a) are interglacial times at present, and about 100,000, 200,000, 300,000; 400,000 years and older that occur about every 100,000 years. Longer glacial periods occur between interglacial periods. Graphs b–d are over time periods of 100,000 years to 100 years. The rapid rise from about 1900 to 2008 of nearly 0.9°C is shown in (e). Note the very rapid rise, since about 1970, of about 0.2°C per decade. See text for further explanation. *(Modified after University Corporation for Atmospheric Research, Office for Interdisciplinary Studies. 1991. Science capsule, Changes in time in the temperature of the earth.* EarthQuest *5(1); and the UK Meteorological Office. 1997.* Climate Change and Its Impacts: A Global Perspective*)*

temperatures have coincided with major glacial events that have greatly altered the landscape; high temperatures are associated with interglacial conditions. Interglacial and glacial events become increasingly prominent in the scales, showing changes over 150,000 and 18,000 years. The last major interglacial warm period, even warmer than today, was the Eemian (Figure 18.18b). During the Eemian, sea level was a few meters higher than it is today. The cold period that occurred about 11,500 years ago is known as the Younger Dryas, followed by rapid warming to the Holocene maximum, which preceded the Little Ice Age (Figure 18.18c).

A scale of 1,000 years shows several warming and cooling trends that have affected people (Figure 18.18d). For example, a major warming trend from approximately A.D. 1100–1300 allowed the Vikings to colonize Iceland, Greenland, and northern North America. When glaciers made a minor advance around A.D. 1400, during a cold period known as the Little Ice Age, the Viking settlements in North America and parts of Greenland were abandoned.

In approximately 1750, an apparent warming trend began that lasted until approximately the 1940s, when temperatures cooled slightly. Over the past 140 years, more changes are apparent, and the 1940s event is clearer (Figure 18.18e). It is evident from the record that, in the past 100 years, global mean annual temperature has increased by approximately 0.8°C (1.4°F). Most of the increase has been since the 1970s, and the 1990s and first 8 years of the twenty-first century had the warmest temperatures since global temperatures have been monitored.[7,13] This period may become known as the early twenty-first century increase in global temperature. **Table 18.1** lists evidence of the recent warming.

Why Does Climate Change?

The question that begs to be answered is: Why does climate change? Examination of Figure 18.18 suggests that there are cycles of change lasting 100,000 years, separated by shorter cycles of 20,000 to 40,000 years. These cycles were first identified by Milutin Milankovitch in the 1920s as a hypothesis to explain climate change. Milankovitch realized that the spinning Earth is like a wobbling top, unable to keep a constant position in relationship to the Sun; this instability partially determines the amount of sunlight reaching and warming Earth. Milankovitch discovered that variability in Earth's orbit around the Sun follows a 100,000-year cycle that is correlated with the major glacial and interglacial periods shown on Figure 18.18a. Earth's orbit varies very slightly from a nearly circular ellipse to a more elongated ellipse. Over the 100,000-year cycle of Earth, when the orbit is most elliptical, solar radiation reaching Earth is greater than during a more circular orbit. Cycles of approximately 40,000 and 20,000 years result from changes in the tilt and wobble of Earth's axis, respectively. *Milankovitch cycles* reproduce most of the long-term cycles observed in the climate, and they have a significant effect on climate. However, the cycles are not sufficient to produce the observed large-scale global climatic changes. Therefore, these cycles, along with other processes, must be invoked to explain global climatic change. Thus, the Milankovitch cycles that force (i.e., push) the climate in one direction or another can be looked at as natural processes (i.e., forcing) that, when linked to other processes, produce climatic change.[14,15] We now will consider this forcing concept in more detail.

Climate forcing is defined as an imposed change of Earth's energy balance. The units for the forcing are W/m^2 and can be positive if a particular forcing increases global mean temperature or negative if temperature is decreased. For example, if the energy from the Sun increases, then Earth will warm (this is positive climate forcing). If CO_2 decreases, causing Earth to cool, that is an example of negative climate forcing.[15] *Climate sensitivity* refers to the response of climate to a specific climate forcing after a new equilibrium has been established, and the time required for the response to a forcing to occur is the *climate response time*.[16] A significant implication of climate forcing is that, if small climate forcing is maintained for a long enough time, large climate change can occur.[12] **Figure 18.19** shows the climate forcing that produced the last major ice age 22,000 years ago (i.e., the last glacial maximum).[6,16] Notice that 1 W/m^2 produces a temperature change of about 0.75°C. Climate forcing in the industrial age is

TABLE 18.1 Evidence Supporting the Early Twenty-First Century Rise in Global Temperature

Warming since the mid-1970s has been about three times as rapid as in the preceding century.
The decade from 2000 to 2009 was the warmest decade on record since measurements have been taken (the instrumental period) and the past 1,000 years, according to geologic data.
The warmest year on record was 2005, with 2002, 2003, 2006, 2007, and 2009 virtually tied for second. The year 2010, when the data has been analyzed, will likely be the warmest on record.
In 2003, the United States was cooler and wetter than average in much of the eastern part of the country, and it was warmer and drier in much of the west. Ten western states were much warmer than average; New Mexico had its warmest year. Alaska was warmer in all four seasons and had one of its 5 warmest years since the state began taking measurements in 1918.
Europe, in 2003, experienced summer heat waves, with the warmest seasonal temperatures ever recorded in Spain, France, Switzerland, and Germany. Approximately 15,000 people died in heat waves in Paris during the summer.
Warm conditions, along with drought, in 2003 contributed to severe wildfires in Australia, southern California, and British Columbia, Canada.
2008 was the coolest year since 2000, but it was still the tenth-warmest year since 1880. The 11 warmest years on record have occurred during the 13-year period from 1997 to 2009.
Since 1965, the average temperature of Earth at the surface has increased about 0.2°C per decade.[6,7]

Note: A few years of high temperatures with drought, heat waves, and wildfires are not by themselves an indication of longer-term global warming. The persistent trend of increasing temperatures over several decades is more compelling evidence that global warming is real and happening.
Global temperature data from the United States (NOAA) and Europe (WMO).

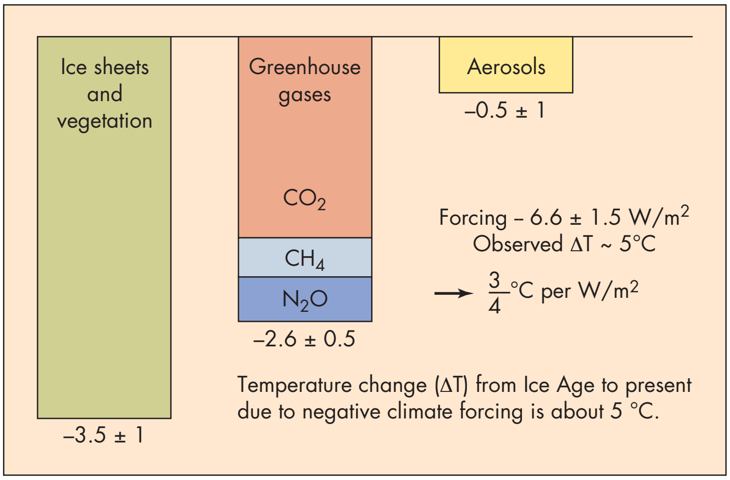


FIGURE 18.19 Climate forcing (W/m^2) during the last ice age Total negative forcing that helped produce the ice age was about −6.6 W/m^2. *(Modified after Hansen, J. 2003.* Can We Defuse the Global Warming Time Bomb? *Edited version of presentation to the Council on Environmental Quality, June 12, Washington, DC; and Natural Science, www.naturalscience.com)*

shown in **Figure 18.20**. Total positive forcing is about 1.6 W/m^2, most of which is due to greenhouse gas (CO_2, CH_4, N_2O) forcings. Rates of emissions of these gases are shown in Figure 18.16. They have increased dramatically in the past 100 years.[7,11,13]

We now believe that our climate system may be inherently unstable and capable of changing quickly from one state to another in as short a time as a few decades.[17] However, very short or abrupt climate change is unlikely. Part of what may drive the climate system and its potential to change is the *ocean conveyor belt*, a global-scale circulation of ocean waters characterized by strong northward movement of 12° to 13°C (53° to 55°F) near-surface waters in the Atlantic Ocean that are cooled to 2° to 4°C (35° to 39°F) when they arrive near Greenland (**Figure 18.21**, page 637).[17] As the water cools, it becomes saltier; the increase in salinity and cooler water increases the water's density and causes it to sink to the bottom. The current then flows southward around Africa, adjoining the global pattern of ocean currents. The flow in this conveyor belt current is huge, equal to about 100 Amazon Rivers. The amount of warm water and heat released to the atmosphere, along with the stronger effect of relatively warm winter air moving east and northeast across the Atlantic Ocean, is sufficient to keep Northern Europe 5° to 10°C (8.5° to

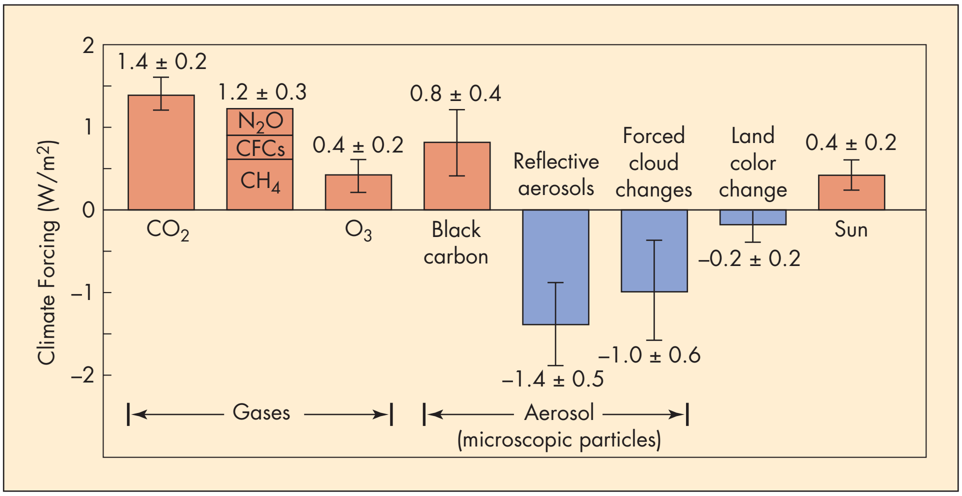


FIGURE 18.20 Climate forcings in the industrial age that started in 1750 Positive forcings (red columns) warm and negative forcings (blue columns) cool. Human-caused forcings in recent years dominate over natural forcings. Total forcing is about 1.6 ± 0.1 W/m^2, consistent with the observed rise in air surface temperature over the past few decades. The vertical bars are known as error bars. See for example C0$_2$, which is 1.4 ± 0.2 W/m^2. This means the true value is most likely between 1.2 and 1.6 W/m^2 or 1.4 ± 0.2. *(Modified after Hansen, J. 2003. NASA Goddard Institute for Space Studies and Columbia University Earth Institute)*

- Increases of greenhouse gases (except O_3) are known from observations and bubbles of air trapped in ice sheets. The increase of CO_2 from 285 parts per million (ppm) in 1850 to 368 ppm in 2000 is accurate to about 5 ppm. The conversion of this gas change to a climate forcing (1.4 W/m^2), from calculation of the infrared opacity, adds about 10% to the uncertainty.

- Increase of CH_4 since 1850, including its effect on stratospheric H_2O and tropospheric O_3, causes a climate forcing about half as large as that by CO_2. Main sources of CH_4 include landfills, coal mining, leaky natural gas lines, increasing ruminant (cow) population, rice cultivation, and waste management. Growth rate of CH_4 has slowed in recent years.

- Tropospheric O_3 is increasing. The U.S. and Europe have reduced O_3 precursor emissions (hydrocarbons) in recent years, but increased emissions are occurring in the developing world.

- Black carbon ("soot"), a product of incomplete combustion, is visible in the exhaust of diesel-fueled trucks. It is also produced by biofuels and outdoor biomass burning. Black carbon aerosols are not well measured, and their climate forcing is estimated from measurements of total aerosol absorption. The forcing includes the effect of soot in reducing the reflectance of snow and ice.

- Human-made reflective aerosols include sulfates, nitrates, organic carbon, and soil dust. Sources include burning fossil fuel and agricultural activities. Uncertainty in the forcing by reflective aerosols is at least 35%.

- Indirect effects of aerosols on cloud properties are difficult to compute, but satellite measurements of the correlation of aerosol and cloud properties are consistent with the estimated net forcing of −1 W/m^2, with uncertainty of at least 50%.

17°F) warmer than it would otherwise be. If the conveyor belt were to shut down, it would have an effect on the climate of Europe. However, the effect would not be catastrophic to England and France in terms of producing extreme cold and ice-bound conditions.[18]

Although scientific uncertainties exist, there is sufficient evidence to state that (1) there is a discernible human influence on global climate; (2) warming is now occurring; and (3) the mean surface temperature of Earth will likely increase by 1.5° to 4.5°C (2.6° to 7.8°F) during the twenty-first century.[6,7] The human-induced component of global warming results from increased emissions of gases that tend to trap heat in the atmosphere. There is good reason to argue that increases in carbon dioxide and other greenhouse gases are related to an increase in the mean global temperature of Earth. Over the past few hundred thousand years, there has been a strong correlation between the concentration of atmospheric CO_2 and global temperature (Figure 18.15). When CO_2 has been high, temperature has also been high, and, conversely, low concentrations of CO_2 have been correlated with a low global temperature. However, in order to better understand global

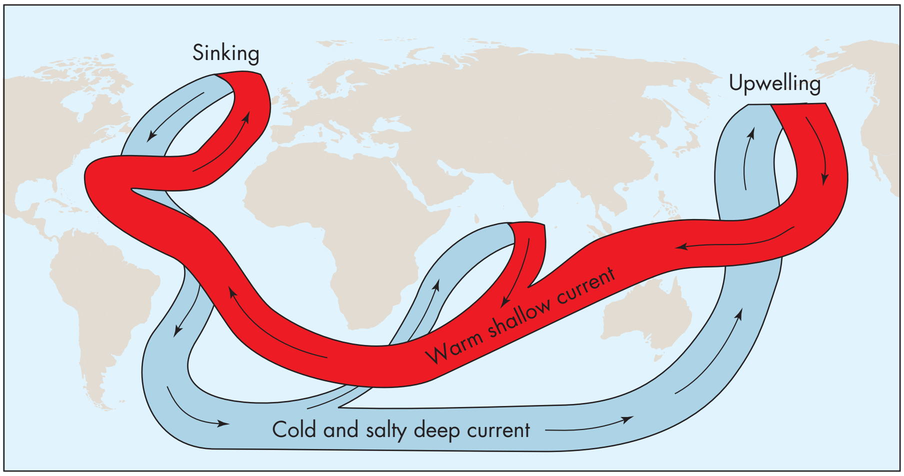


FIGURE 18.21 Ocean conveyor belt Idealized diagram of the ocean conveyor belt. The actual system is more complex, but, in general, warm surface water (red) is transported westward and northward (increasing in salinity owing to evaporation) to near Greenland, where it cools from contact with cold Canadian air. As the water increases in density, it sinks to the bottom and flows south, then east to the Pacific, where upwelling occurs. The masses of sinking and upwelling waters balance, and the total flow rate is about 20 million m^3 (700 million ft^3) per second. The heat released to the atmosphere from the warm water helps keep Northern Europe warmer than it would be if the oceanic conveyor belt were not present. *(Modified after Broecker, W. 1997. Will our ride into the greenhouse future be a smooth one?* Geology Today *7(5):2–6)*

warming, we need to consider major *forcing* variables that influence global warming, including solar emission, volcanic eruption, and anthropogenic input.

Solar Forcing

Since the Sun is responsible for heating Earth, solar variation should be evaluated as a possible cause of climate change. When we examine the history of climate during the past 1,000 years, we see that the variability of solar energy plays a role. Examination of the solar record reveals that the Medieval Warm Period (A.D. 1000–1300) corresponds with a time of increased solar radiation, comparable to that which we see today. Evaluation of the record also suggests that minimum solar activity occurred during the fourteenth century, coincident with the beginning of the Little Ice Age (Figure 18.18d). Therefore, it appears that variability of the input of solar energy to Earth can partially explain climatic variability during the past 1,000 years. However, the effect is relatively small, only 0.25 percent; that is, the difference between the solar forcing from the Medieval Warm Period to the Little Ice Age is only a fraction of 1 percent.[19] Brightening of the Sun is unlikely to have had a significant effect on global warming since the beginning of the Industrial Revolution.[20]

Volcanic Forcing

Upon eruption, volcanoes can hurl vast amounts of particulate matter, known as aerosols, high (15 to 25 km) into the atmosphere. The aerosol particles are transported around Earth by strong winds. They reflect a significant amount of sunlight and produce a net cooling that may offset much of the global warming expected from the anthropogenic greenhouse effect.[7,21] For example, increased atmospheric aerosols over the United States (from air pollution) are probably responsible for mean temperatures roughly 1°C (1.7°F) cooler than they would be otherwise. Aerosol particle cooling may, thus, help explain the disparity between model simulations of global warming and actual recorded temperatures that are lower than those predicted by models.[22]

Volcanic eruptions add uncertainty in predicting global temperatures. For instance, what was the cooling effect of the 1991 Mt. Pinatubo eruption in the Philippines (**Figure 18.22**)? Tremendous explosions sent volcanic ash to elevations of 30 km (19 mi) into the stratosphere, and, as with similar past events, the aerosol cloud of ash and sulfur dioxide remained in the atmosphere, circling Earth, for several years. The particles of ash and sulfur dioxide scattered incoming solar radiation, resulting in climatic forcing of about 3 W/m^2, cooling Earth about 2.3°C in 1991 and 1992. Calculations suggest that aerosol additions to the atmosphere from the Mt. Pinatubo eruption counterbalanced the warming effects of greenhouse gas additions through 1992. However, by 1994, most aerosols from the eruption had fallen out of the atmosphere, and global temperatures had returned to previous higher levels.[23] Volcanic forcing from pulses of volcanic eruptions is believed to

FIGURE 18.22 Volcanic eruption cools Earth The eruption of Mt. Pinatubo in the Philippines in 1991 injected vast amounts of volcanic ash and sulfur dioxide up to about 30 km (19 mi) into the atmosphere. *(T. J. Casadevall/USGS)*

have significantly contributed to the cooling of the Little Ice Age (see Figure 18.18d).[19]

Anthropogenic Forcing

Evidence of anthropogenic climate forcing, resulting in a warmer world, is based in part on the following:

- Recent warming over the past few decades of 0.2°C per decade cannot be explained by natural variability of the climate over recent geologic history.
- Industrial-age forcing of 1.6 W/m^2 (Figure 18.20) is mostly due to emissions of carbon dioxide that, with other greenhouse gases, have greatly increased in concentration in the past few decades (Figure 18.16).
- Climate models suggest that natural forcings in the past 100 years cannot be responsible for what we know to be a nearly 1°C rise in global land temperature (Figure 18.4b). When natural and anthropogenic forcing are combined, the observed changes can be better explained.

Present warming greatly exceeds the natural variability (i.e., climate forcing) and closely agrees with the response predicted from models of greenhouse gas forcing.[7]

Human processes are also causing a slight cooling. Reflection from air pollution particles (i.e., aerosols) has reduced incoming solar energy by as much as 10 percent. This is termed **global dimming**. Negative forcing from aerosols in the industrial age is –1.4 W/m^2 (Figure 18.20) and may be offsetting up to 50 percent of the expected warming due to greenhouse gases.

18.6 Potential Effects of Global Climate Change

Our discussion of global warming can be summarized as follows: (1) Human activity is increasing the concentration of greenhouse gases in the atmosphere; (2) the mean temperature of Earth increased by about 0.8°C (1.4°F) in the past 100 years; and (3) a significant portion of the observed increase in the mean temperature of Earth results from human activity.

All climate models are consistent in predicting that warming will continue, due to greenhouse gases now in the atmosphere, and possibly accelerate in the coming decades. That holds true even if greenhouse gas emissions by people are nearly eliminated; warming of about 0.5 to 1.0°C would still occur in coming decades. Therefore, we need to carefully examine the potential effects of such warming.

If the level of carbon dioxide in the atmosphere doubles from pre-industrial levels, as expected, it is estimated that the average global temperature will rise about 1.5° to 4.5°C (2.6° to 7.8°F), with significantly greater warming at the polar regions.[7] Specific effects of this temperature rise in a specific region are difficult to predict, but likely possibilities include increased melting of glacial and sea ice, thawing of permafrost, change in the global climate pattern, and rise in sea level.

Glaciers and Global Warming

A **glacier** is a land-bound mass of moving ice. Glaciers of all sizes are an important agent of erosion and landscape development. We will begin our discussion here with the form and process of glaciers and

topics related to the cold climate: permafrost and windblown silt.

Glaciers and the Cold-Climate Phenomenon. The cold-climate phenomenon of ice has become an important environmental topic. As more people live and work in the higher latitudes, we will have to learn more about regions of glaciation and permafrost to ensure the best use of these sometimes fragile environments.

Glaciation. Glacial ice forms as snow accumulates over a period of years, is compressed from the weight of overlying snow, and recrystallizes as a granular ice known as *firn*. Loose snow is, by volume, about 90 percent air compared to firn, which is about 25 percent air. With further recrystallization, firn is changed to blue glacial ice with less than 20 percent air by volume. Some of the air in glacial ice is present as air bubbles. Air trapped in bubbles are samples of the atmosphere from the past when the snow fell. The process of transformation from snow to glacial ice may take tens to thousands of years.

Glaciers that cover large tracts of land are called *continental glaciers*, or *ice sheets*; those confined to mountain valleys at high altitudes or latitudes are called *mountain* (or *alpine*) *glaciers*. Only a few thousand years ago, the most recent continental glaciers retreated from the Great Lakes region of the United States. Several times in the past 2.6 million years, during the epoch known as the Pleistocene or Ice Age (see the geologic time scale in Table 1.1), the ice has advanced southward. Ice sometimes covered as much as 30 percent of the land area of Earth, including the present sites of major cities such as New York and Chicago (**Figure 18.23**).

Today, glacial ice covers only about 10 percent of the land area of Earth. Most of this ice is located in the Antarctic ice sheet (**Figure 18.24**), with lesser amounts in the Greenland ice sheet and in the mountain glaciers of Alaska, southern Norway, the Alps, and the Southern Alps in New Zealand (**Figure 18.25**, page 641). Scientists are still speculating about whether the continental ice sheets will advance once again. We may, indeed, still be in the Ice Age.

Glaciers typically move less than 1 m per day, and many move only a few centimeters per day. However, Alaskan glaciers have quite irregular rates of advance and retreat. For example, the Black Rapids Glacier advanced several kilometers down its valley in a period of only 5 months in 1936 and 1937, and then it started to retreat. Such a rapid advance, called a *glacial surge*, can radically change a local environment.

Glaciers move by several processes, including basal sliding over water-saturated sediment ice and rock. An increase in the water at the base of a glacier can result in a glacier surging. Glaciers also move by internal flow that results from deformation and recrystallization of ice. Glacial ice below a depth of about 60 m can deform plastically like Silly Putty. At shallow depths, glacial ice behaves as a brittle material (like rock). It is in the brittle zone that crevasses (i.e., open cracks) form. As the glacial ice moves, different types of crevasses form. These can be several

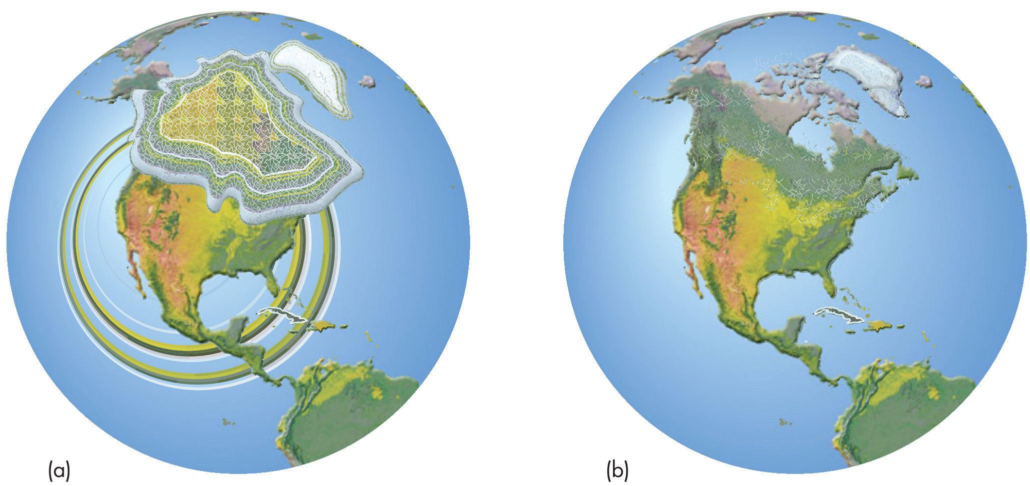
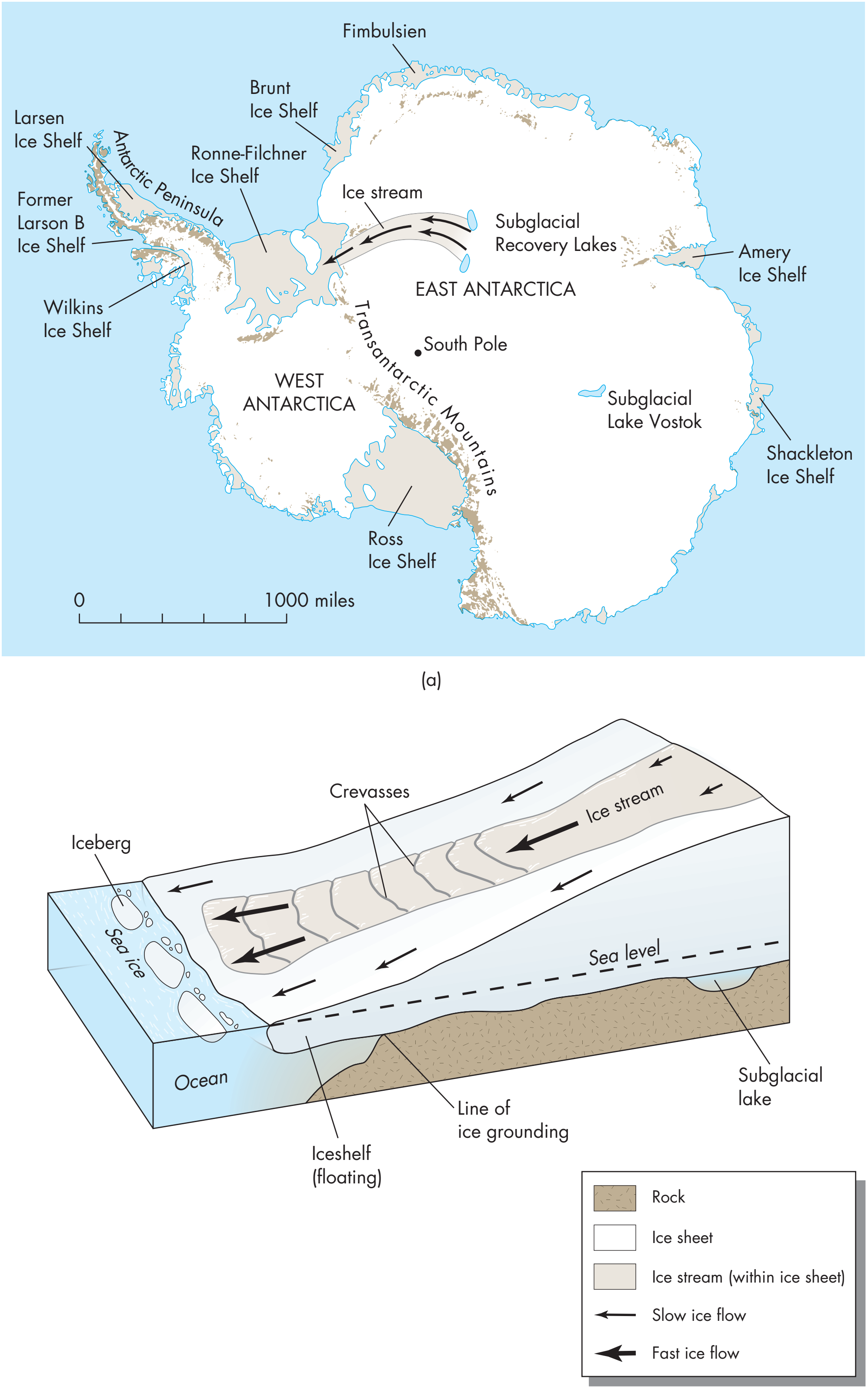


FIGURE 18.23 Maximum extent of ice sheets Ice sheets (a) about 21,000 years ago (late Pleistocene) and (b) today. *(NOAA)*

FIGURE 18.24 Antarctic ice sheet (a) Map of Antarctica (area about 1.4 times that of the United States) showing ice sheets, ice shelves, and ice-free rock areas (mountains). Also shown are subglacial Lake Vostok (15,700 km^2) and Recovery Lakes. More than 150 subglacial lakes have been discovered. Some ice streams start above subglacial lakes such as the Recovery Lakes. Water spilling from lakes and other thermal processes could reduce friction and cause the ice to flow faster, from about 3 m per year upstream of a subglacial lake to 20 to 30 m per year downstream of a lake. *(U.S. Geological Survey and British Antarctic Survey. http://lima.usgs.gov. Accessed 3/8/08)* (b) Idealized diagram of an ice stream. The ice shelf helps buttress (i.e., stabilize) the ice flowing toward the ocean. If this buttress is lost, the ice sheet would move faster toward the sea. Global warming is believed to be influencing ice shelf collapse. For example, in 2002, about 5,000 km^2 of the Larson B ice shelf collapsed, and, in 2008, about 500 km^2 of the Wilkins Ice Shelf collapsed. *(Modified after Bell, R. E. 2008.* Scientific American *298(2):64; and Appenzeller, T. 2007.* National Geographic *211(6):65)*



(a)

(b)

FIGURE 18.25 Confluence of Muldrow and Traleika glaciers below Mount Denali, Alaska The dark material on the glaciers is sediment being carried on the top of the ice. The dark material down the glacier from the confluence is a medial moraine. A moraine is composed of rock debris deposited by glacial ice along glacier margins (i.e., lateral moraine), beneath glaciers (i.e., ground moraine), and in front of glaciers (i.e., recession, or terminal, moraine). The medial moraine formed when two lateral moraines merged at a confluence. The fractures in the white glacier ice are crevasses. *(Michael Collier)*

kilometers long and tens of meters deep, presenting a hazard to people crossing a glacier.

There have been important recent discoveries about the dynamics of moving ice on the ice sheets of Antarctica and Greenland. Subglacial lakes in Antarctica lubricate the base of the ice, causing it to move faster in ice streams within the larger ice sheet (Figure 18.24). Most of the ice transported from the interior of Antarctica to the coast was transported by ice streams. On Greenland, there is surface water from ice melted by warming air in the summer. Meltwater flows rapidly down crevasses, melting the ice down to the bedrock below (**Figure 18.26**). At the base of the ice sheet, the water lubricates the ice, and it flows faster.[24–26] As more people move into areas that are still partly glaciated, we will have more situations in which human use of the land comes into conflict with glacial processes, as, for example, floods produced when subsurface water in glaciers is suddenly released.

Continental and mountain glaciers have produced a variety of depositional and erosional landforms that are easily seen in the landscape. Glacial deposits of Earth materials are prominent characteristics of many regions. For example, the flat, nearly featureless *ground moraine*, or *till plains*, of central Indiana are composed of till, material carried and deposited by the continental glaciers that completely buried preglacial river valleys. It is difficult to believe that beneath these glacial deposits is a topography formed by running water, much like the hills and valleys of southern Indiana that glaciers never reached.

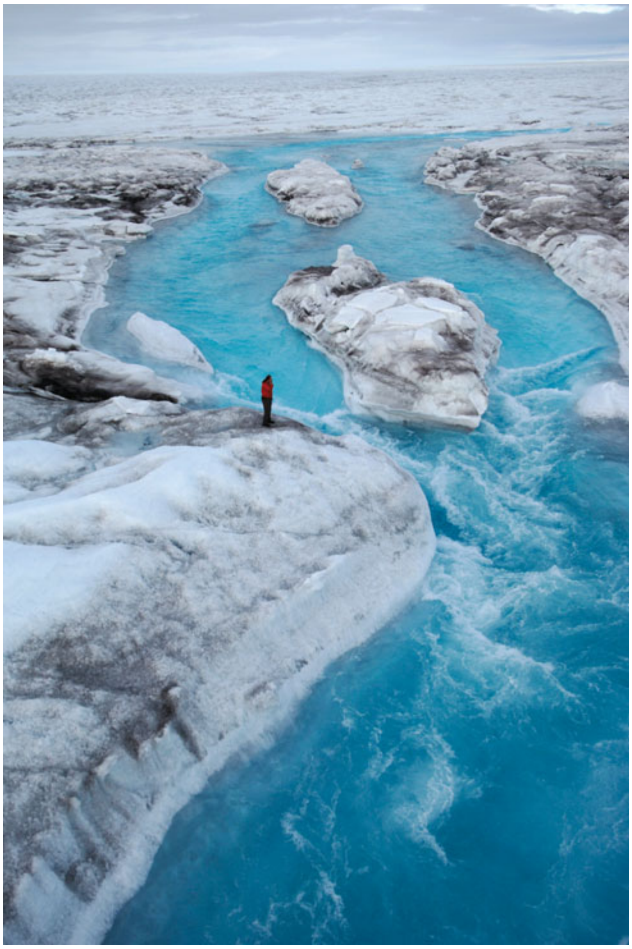


FIGURE 18.26 Surface water on Greenland ice sheet Water flows into a crevasse to the base of the ice, where it causes ice to flow faster. *(James Balag)*

Till is heterogeneous material deposited directly by the ice; it may include, for example, boulders, gravel, sand, silt, and clay particles. In addition to till, glacial deposits include *outwash*, material carried away from glaciers by meltwater in streams. Outwash consists of materials such as silt, sand, and gravel.

Finally, deposition of glacial deposits favors the formation of lakes. Blocks of glacial ice frequently are incorporated with glacial deposits. When a large ice block melts, a depression may form at the surface that fills with water, forming a shallow pond or lake. These lakes may be short-lived and soon fill with sediment and decaying vegetation (i.e., water plants). As the plants are buried, they may be transformed to high organic soils or peat deposits. Such deposits are mined for peat from areas glaciated during the Pleistocene in the midwestern United States.

Glaciers are also agents of erosion:

- The Great Lakes in the United States are in part due to glacial erosion of preglacial lowlands.
- Alpine or valley glaciers can convert V-shaped valleys formed by river erosion to U-shaped ones (**Figure 18.27**).
- Alpine glaciers can form sharp peaks, or "horns" (e.g., the Matterhorn in France), or sharp ridge lines (e.g., the Italian Alps, the Dolomites).
- Glacial erosion can carve grooves or shallow furrows in rock, showing the direction the glaciers move. Examples of these features can be viewed in Central Park in New York City.
- Glacial erosion near where continental glaciers form, as, for example, in Canada, has removed vast quantities of rock debris and transported them south, to be deposited as glacial till. This explains the occasional find of gem-quality diamonds in Indiana streams (they came from Canada!).

Because glaciation produces such a variety of landforms, the environmental geology of a recently glaciated area may be complex. The wide variety of Earth materials found in an area recently glaciated requires that detailed evaluation of the physical properties of surficial and subsurface materials be conducted before planning, designing, and building structures such as dams, highways, and large buildings. For example, if glacial lake deposits and peat are present, differential subsidence of the ground upon loading (i.e., building a heavy structure) is a real possibility.

Permafrost. Permanently frozen ground, or *permafrost*, is a widespread natural phenomenon in the higher northern latitudes above about 60°, underlying about 20 percent of the land area in the world (**Figure 18.28**). Two main types of permafrost, called *discontinuous* and *continuous*, are defined based on the areal extent of frozen ground. In the *continuous permafrost* areas of Greenland and northernmost Asia and North America, the only ice-free ground is beneath deep lakes or rivers. The water keeps the ground from freezing. Farther south is the region of *discontinuous permafrost*, characterized in its higher latitudes by scattered islands of thawed ground in a predominantly frozen area. The

(a) (b)

FIGURE 18.27 Glaciated valley (a) V-shaped valley formed by river erosion, Yellowstone River, Wyoming. *(Betty Crowell/Faraway Places)* (b) U-shaped valley scoured by glacier ice, Sierra Nevada, California. *(Michael Collier)*

FIGURE 18.28 Tundra landscape north of the Arctic Circle. Thawing of tundra and associated permafrost has accelerated in recent decades. *(Superstock)*

percentage of unfrozen ground increases at lower latitudes, until finally, at the southern border of the permafrost, all the ground is unfrozen.

Permafrost varies from north to south in thickness as well as in continuity. About 85 percent of Alaska is underlain by continuous or discontinuous permafrost that varies in thickness from about 400 m in the north to less than 0.3 m at the southern margin of the frozen ground.[27] A cross section of permafrost shows an upper active layer that thaws during the summer, as well as unfrozen layers within the permafrost below the active layer. The thickness of the active layer depends upon such factors as exposure, surface slope, amount of water, and, particularly, the presence or absence of a vegetation cover, which greatly affects the thermal conductivity of the soil. When vegetation is removed, the surface soil is no longer insulated from solar radiation, and the permafrost may thaw.

Special engineering problems are associated with the design, construction, and maintenance of roads, railroads, airfields, pipelines, and buildings in permafrost areas. The vast range of problems occurring in different Earth materials in these areas is beyond the scope of our discussion. In general, the major concerns are associated with permafrost in silty (i.e., fine-grained), poorly drained materials. Because these materials hold a good deal of frozen water, they produce a lot of water upon melting. Thawing produces unstable materials, resulting in settling, subsidence, landslides, and lateral or downslope flowage of saturated sediment. Heaving (i.e., rising) and subsidence of the ground caused by freezing and thawing of the active layer are responsible for many of the engineering problems in the arctic and subarctic regions.[27]

The presence of permafrost has led to very high maintenance costs and relocation or abandonment of highways, railroads, and other structures (**Figure 18.29**). Gravel roads may experience severe differential subsidence (i.e., sinking at the surface) caused by thawing of permafrost. On the North Slope of Alaska, tractor trails constructed by bulldozing off the vegetation cover over permafrost have caused problems. Small ponds on abandoned trails often form during the first summer following the trail construction, and they continue to grow deeper and wider as the permafrost continues to thaw.[27]

Loess. Windblown deposits are generally subdivided into two groups: sand deposits (mainly dunes) and *loess*, which is windblown silt. Extensive deposits of windblown sand and silt cover thousands of square kilometers in the United States. Sand dunes are discussed with changing climate pattern; here we consider windblown silt.

In contrast to sand, which seldom moves more than 1 m off the ground, windblown silt and dust can be carried in huge dust clouds thousands of meters in altitude. A typical dust storm 500 to 600 km in diameter may carry more than 100 million tons of silt and dust, sufficient to form a pile 30 m high and 3 km in diameter. Terrible dust storms in the 1930s probably exceeded even this, perhaps carrying more than 58,000 tons of dust per square kilometer.

Most of the loess in the United States is located in and adjacent to the Mississippi Valley, but some is found in the Pacific Northwest and Idaho. It is derived primarily from glacial outwash—that is, from material deposited by streams carrying glacial meltwater during the ice age. The retreat of the glaciers

(a) (b)

FIGURE 18.29 Permafrost damage (a) Damage to a house resulting from subsidence due to thawing of permafrost as a result of poor construction practices in Alaska. *(Steve McCutcheon/Anchorage Museum of History & Art)* (b) Severe differential subsidence of a gravel road near Umiat, Alaska, caused by thawing of ice-wedge polygons in permafrost. *(O. J. Ferrians/USGS)*

left behind large unvegetated areas adjacent to rivers. These areas were highly susceptible to wind erosion, so silt in the outwash was blown away and redeposited as loess. We know this because loess generally decreases rapidly in thickness in proportion to distance from major rivers, including the Mississippi, Missouri, Illinois, and Ohio. Loess deposits may be *primary loess*, which has been essentially unaltered since being deposited by the wind, or *secondary loess*, which has been reworked and transported a short distance by water or intensely weathered in place.

Although loess is strong enough to form nearly vertical slopes, it rapidly consolidates when subjected to a load (e.g., a building) and wetted. This process, called *hydroconsolidation*, occurs when the clay films or calcium carbonate cement around the silt grains wash away. Loess may therefore be a dangerous foundation material. Settling and cracking of a house built on loess reportedly took place overnight when water from a hose was accidentally left on.

Melting of Glacial Ice and Sea Ice and Thawing of Permafrost with Global Warming. Today there is concern that global warming is resulting in accelerated melting of glacial ice of the Greenland ice sheet and mountain glaciers. The latter are of particular importance in Europe and South America as water resources for people and ecosystems further down the mountain. In Bolivia, a 70-year-old ski resort on a glacier is all but shut down because a small glacier on which the ski runs are built has all but disappeared.

Currently, many glaciers in the Pacific Northwest of the United States, as well as in Europe, China, and Chile, are retreating or decreasing more, in terms of thickness of ice (typically 10 to 30 percent of ice thickness since 1977), than are advancing or increasing in thickness.[26,28] The increase in the number of retreating glaciers is accelerating in the Cascades, Switzerland, and Italy. Evidently, this acceleration is in response to the mean global temperature averaging 0.4°C (0.68°F) above the long-term mean temperature during the years 1977 to 1994. On Mt. Baker in the Northern Cascades, for example, all eight glaciers were advancing in 1976. By 1990, all eight were retreating. In addition, 4 of 47 alpine glaciers observed in the Northern Cascades have disappeared since 1984. Most of the glaciers in Glacier National Park may be gone by 2030 (**Figure 18.30**) and those of the European Alps by the end of the century.[26,28,29]

Melting of the ice of the Greenland ice sheet has doubled since about 1998. Melting produces surface water that flows through openings and fractures (i.e., crevasses) and down to the base of the glacier, where it lubricates the bottom of the ice, resulting in an acceleration of glacial movement. Most glaciers in the southern half of the Greenland ice sheet are accelerating and losing ice more rapidly than previously. In 2005 alone, about 200 km^3 (50 mi^3) of glacial ice was lost from this sheet.[26]

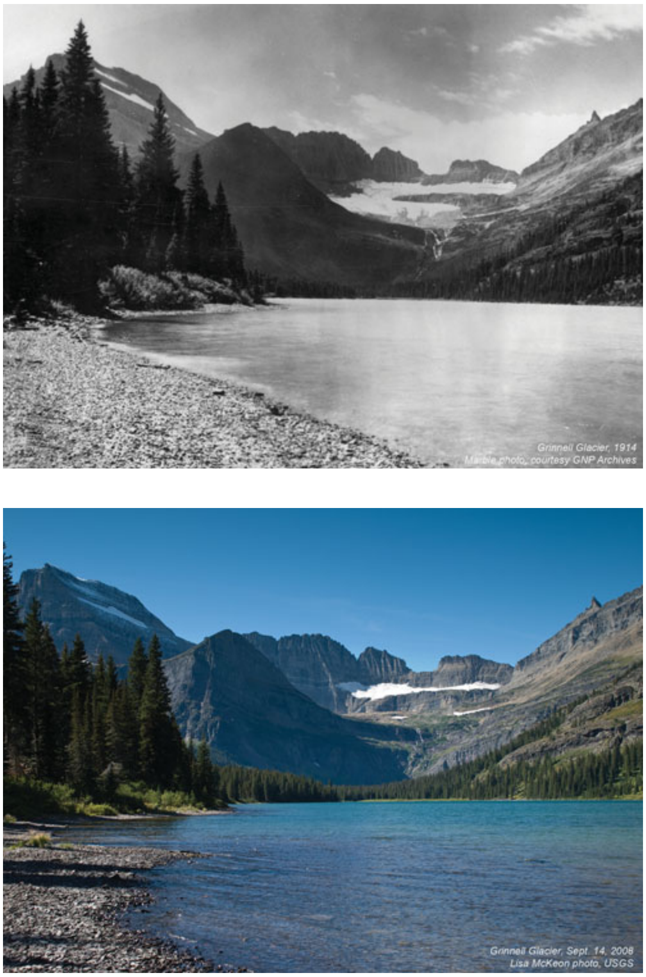


FIGURE 18.30 Grinnell Glacier, 1940 and 2006
(Glacier National Park/USGS)

When glacial ice melts and bare ground is exposed, there is a positive feedback because white ice reflects sunlight (while absorbing less sunlight), while darker rock reflects less sunlight (while absorbing more sunlight). The more ice that melts, the faster the warming and increased melting. This is a classic *positive feedback cycle*—warming leading to more warming. This explains, in part, why warming at higher latitudes and elevations may exceed other areas.[7]

Sea ice in the Arctic Ocean is declining in area. Since the 1970s, when satellite remote sensing became possible, ice coverage in September (when sea ice is at a minimum) has declined about 11 percent per decade. 2007 was the year with the lowest extent of sea ice was (**Figure 18.31**). The rapid decline in 2007 was partly in response to atmospheric circulation that favored melting. There is concern that the arctic is in a transitional phase toward a seasonal ice-free condition by 2030.[30]

The Antarctic Peninsula, relatively narrow land that points toward South America, is known to be one of the most rapidly warming regions on Earth. New studies suggest that the warming extends well beyond the peninsula to include most of West Antarctica. Although the trend is partly offset by cooling of East Antarctica in the autumn, the trend for Antarctica is positive climate forcing, resulting in warming. The causes of warming are complex, but they require changes in atmospheric circulation with temperature changes (e.g., warmer sea surface water and sea ice). The most likely direct cause is

FIGURE 18.31 Arctic sea ice (minimum), 1953–2007 Rapid decline in 2007 was partly due to atmospheric circulation that favored melting. *(Stroeve, J., et al. 2008. Arctic sea ice extent plummets in 2007.* EOS, Transactions, American Geophysical Union *89(2):12–14)*

anthropogenic greenhouse gas forcing, resulting from increasing concentrations of greenhouse gases in the atmosphere.[31]

As Earth warms, more snowfall on Antarctica is predicted. Satellite measurement from 1992 to 2003 suggested that the East Antarctic ice cap on Antarctica increased in mass during the period of measurement by about 50 billion tons per year[32]. (This is a very small amount, given the enormous size of Antarctica; it represents less than 0.5 percent of Antarctica, covered to a depth of 1 m.) Another study, using computer simulation and ice core records, reported that there has been no statistically significant increase in snowfall over Antarctica since the 1950s, suggesting that there is no reduction of sea-level rise by increased Antarctic snowfall, nor an increase in mass of glacial ice that would store water.[33] What is clear is that Antarctica is a complex place where more basic data research is needed to better understand the consequences of global warming.

Permafrost is widespread in the arctic (Figure 18.28), and as the arctic warms, thawing of permafrost is occurring. Thawing permafrost in Siberia and Canada is releasing carbon dioxide (CO_2) and methane (CH_4) that are trapped in the permafrost. The frozen ground becomes a swamp rich in carbon dioxide and methane. Both CO_2 and CH_4 are greenhouse gases, and there is positive feedback occurring. As the arctic warms, more permafrost thaws, releasing more greenhouse gases, which causes more warming. Permafrost covered with snow has a high reflectivity (i.e., albedo), but thawed permafrost has a lower reflectivity, and more solar energy is absorbed, which facilitates further thawing of the permafrost (i.e., another positive feedback loop).[34]

Climate Patterns

A global rise in temperature might significantly change rainfall patterns, soil moisture relationships, and other climatic factors that are important to agriculture. (See A Closer Look: Desertification.) It has been predicted that some northern areas, such as Canada and Eastern Europe, may become more productive, whereas lands to the south will become more arid. It is important to emphasize that such predictions are very difficult to make in light of the uncertainties surrounding global warming. Furthermore, the northward movement of optimal climatic growing zones does not necessarily mean that prime agricultural zones will move north, since maximum grain production is also dependent on fertile soil conditions that may not be present in all new areas. For example, Canadian prairie soils tend to be thinner and less fertile than those of the midwestern United States. To some extent, it is this uncertainty that concerns people. Stable or expanding global agricultural activities are crucial to people throughout the world who depend upon the food grown in the major grain belts. Hydrologic changes associated with climatic change resulting from global warming might seriously affect food supplies worldwide. In California and the San Joaquin Valley, where much of the fruits and vegetables for the United States are raised, there may be less available water. Much of the irrigation water comes from runoff from spring snowmelt in the Sierra Nevada to the east of the valley. With global warming, winter rainfall will likely increase, but the snowpack will be less. As a result, runoff will be more rapid, filling reservoirs before it is needed to irrigate crops. Water may have to be released from filled reservoirs and lost to the sea.

Global warming might also change the frequency and intensity of violent storms, and this change may be more important than the issue of which areas become wetter, drier, hotter, or cooler. Warming oceans will feed more energy into high-magnitude storms, such as hurricanes. More or larger hurricanes would increase the hazard of living in low-lying coastal areas, many of which are experiencing rapid growth of human population.

That global and regional climatic changes have a significant effect on the incidence of hazardous natural events such as storm damage, landslides, drought, and fires is sometimes dramatically illustrated by El Niño. **El Niño** is a natural climatic event that occurs an average of once every few years, most recently in 1997–1998. El Niño is both an oceanic and an atmospheric phenomenon, involving unusually high surface temperatures in the eastern equatorial Pacific Ocean and droughts and high-intensity rainstorms in various places on Earth (see A Closer Look: El Niño).

Sea-Level Rise

A rise of sea level is a potentially serious problem related to global warming. Global ocean temperature to a depth of at least 3 km has increased since 1961. In this time, the oceans of the world have absorbed

A CLOSER LOOK

Desertification

Arid Lands

One of the major concerns of global warming is the change in regional and global climate patterns, especially the expansion of arid lands and accompanying desert processes.

Arid and semiarid regions of Earth, also known as the dry lands, occupy approximately 35 percent of Earth's land surface. Approximately 20 percent of the world's human population lives there; clearly, dry lands are environmentally important to people.[35]

Arid and semiarid regions of Earth are areas of relatively low to very low amounts of annual precipitation. In some very arid areas, years may pass before any measurable precipitation occurs.

Deserts owe their origin, regardless of their landscape characteristics, to their scant precipitation. The deserts of the world are primarily located in two belts located between 15° and 30° latitude north and south of the equator. These dry belts are caused by the global pattern of atmospheric circulation. At the equator, warm air rises and moves north and south, toward the cooler poles. There are areas of descending air at approximately 30° latitude (see Figure 18.6). Semipermanent cells of high pressure exist in these locations, along with reduced rainfall. The high rainfall at the equator results from rising warm, moist air that cools as it rises and condenses to form rainfall. In the subtropical areas, at approximately 15° to 30° latitude, the air is subsiding rather than rising, so little rain is produced.[36,37]

Global circulation of air masses explains the major deserts of the world, including those in Africa, the Middle East, parts of India, South America, Australia, and North America; however, it is not responsible for all of the deserts of the world. Some of the semiarid lands and deserts of North America, as well as of central Asia, are dry lands because of their position far inland in continents. Dry lands may also occur in the rain shadows of mountain ranges that intercept the rainfall and block storms from moving farther inland.[38] Mountains, hills, plains, normally dry river channels, and alluvial fans are the dominant landforms of arid regions; sand dunes, while locally and even in some cases regionally abundant, are not nearly as abundant. However, sand dunes are interesting and have been romanticized in many a story and movie. When we think of a desert, we may envision *Arabian Nights*, with people and goods marching on camels across the dunes. In reality, most of the time they would be crossing dune-free hills and mountains.

Sand Dunes. Sand dunes and related deposits are found along the coasts of the Atlantic and Pacific Oceans and the Great Lakes. Inland sand is found in areas of Nebraska, southern Oregon, southern California, Nevada, and northern Indiana, as well as along large rivers flowing through semiarid regions—for example, the Columbia and Snake rivers in Oregon and Washington. *Sand dunes* are constructed under the influence of wind from sand moving close to the ground. Simple dunes have a gentle upwind slope and a steep (~33°) downwind slope called the *slip face*. When the wind blows, sand moves up the gentle slope and down the slip face, causing the dune to move in the direction of the wind. The process is known as *dune migration*. Dunes have a variety of sizes and shapes and develop under a variety of conditions. Regardless of where they are located, how they form, or whether they are active or relic (i.e., formed in the past but no longer active) or otherwise stabilized, they tend to cause environmental problems. Migrating sand is particularly troublesome, and stabilization of sand dunes is a major problem in construction and maintenance of highways and railroads that cross sandy areas of deserts. Building and maintaining reservoirs in sand dune terrain is even more troublesome and often extremely expensive. These reservoirs should be constructed only if very high water loss can be tolerated. Canals in sandy areas should be lined to hold water and control erosion.

Desertification

At its simplest, **desertification** may be defined as the conversion of one type of land, such as grasslands, to land that resembles a desert. This conversion does not involve the natural processes associated with climatic changes during the past 2.6 million years that are thought to cause expansion or contraction of desert areas. Rather, desertification is human-induced degradation that introduces desertlike conditions or may transform the land from a particular state to a more desertlike landscape.[35] For example, the Sahara Desert in Africa is expanding (Figure 18.A), as are several other deserts in North America and Asia.

FIGURE 18.A Advancing desert People digging out of a sand dune in the Sahara Desert, Africa, after a windstorm. The Sahara Desert continues to expand. *(Steve McCurry/Magnum Photos, Inc.)*

Two primary characteristics of desertification are degradation of soil, due primarily to soil erosion, and degradation of vegetation.[37] As a result of these two characteristics, the process of desertification may significantly affect the human environment by damaging food production and thereby contributing to malnutrition and famine.[37] Damage and loss of vegetation resulting from desertification may be so extensive that the productivity of the land is essentially lost and may not be recovered in a time frame useful to humans. Therefore, in contrast to drought, which is normally a relatively short-term problem that affects land productivity, desertification involves impacts that are long term and chronic.[35]

For example, consider the U.S. Dust Bowl. Terrible dust storms (Figure 18.B) produced the "black blizzards" of the "Dirty Thirties," better known as the Dust Bowl, that struck the high plains of the United States, particularly Texas, Colorado, Oklahoma, and Kansas. More intensive use of tractors and trucks enabled large-scale farming; farmers cleared the land of vegetation for growing grains. Exceptionally hot and dry drought years also reduced the natural vegetation cover. The exposed topsoil was eroded by wind and covered with sand, frequently generating tremendous dust storms. Thus, both human activity and technology and natural climatic variation played a role in creating the Dust Bowl that severely degraded the farmlands and caused great hardships for the people in the region. Today, northern China is experiencing its own dust bowl, and the causes are similar to those of the United States in the Dirty Thirties—unwise agriculture and grazing practices.

The causes of desertification are well known and recognized. In a general sense, they are related to four main types of poor land use:[36] *overcultivation*, *overgrazing*, *deforestation*, and *poor irrigation practices*. These are exacerbated in some countries with abundant arid and semiarid lands when population increase is rapid. Prevention, minimization, and reversal of desertification involve the following:[39,40]

- Protection and improvement of high-quality land rather than dedication of time and money to poor land
- Application of simple, sound range management techniques to protect the land from overgrazing by livestock
- Application of sound conservation measures to agricultural lands to protect soil resources
- Use of appropriate technology to increase crop production, allowing poorer lands to be returned to less-intensive land uses than intensive agriculture (e.g., forestry, wildlife, grazing)
- Increased land restoration efforts through vegetation management, sand dune stabilization, and control of soil erosion

(a)

(b)

FIGURE 18.B U.S. Dust Bowl (a) Dust storm at Manteer, Kansas, in 1935. *(U.S. Department of Commerce)* (b) Farmer and sons walking into the face of a dust storm, Oklahoma, 1936. Notice that the house is partially buried by dust. *(AP Photo)*

about four-fifths of the heat that has been added to Earth's climate system.[7]

Warming of the oceans causes the water to expand (i.e., thermal expansion), producing a rise in sea level. The rate of sea-level rise due to thermal expansion from 1961 to 2003 is estimated to be about 0.42 ± 0.2 mm per year, increasing to about 1.6 ± 0.5 mm per year from 1993 to 2003. Thus, it appears that sea-level rise due to warming of ocean water is accelerating.[7]

Melting of glacial ice is thought to be contributing to sea-level rise. Melting of sea ice (i.e., floating ice) does not cause a rise in sea level; you can verify this by placing ice in a glass of water and observing the water level in the glass while waiting for the ice to melt. The estimated increase in sea level from melting glaciers is estimated to be about 1.38 ± 0.4 mm per year from 1961 to 2003, increasing to about 1.5 ± 0.6 mm per year from 1993 to 2003.[7]

Several tentative conclusions may be put forth concerning rise in sea level:

- Both thermal expansion and melting glacial ice have contributed significantly to the observed sea-level rise since 1961.
- The difference between the observed and estimated rise in sea level is considerable, suggesting that additional research is needed to better understand sea-level rise.
- The rates of both thermal expansion and melting glacial ice are accelerating.
- The contribution of the Greenland ice sheet to sea-level rise has increased about four times in recent decades, consistent with surface observations of melting glacial ice.

A Closer Look

El Niño

El Niño events probably start from random, slight reductions in the trade winds that, in turn, cause warm water in the western equatorial Pacific Ocean to flow eastward (**Figure 18.C**). This change further reduces the trade winds, causing more warm water to move eastward, until an El Niño event is established.[41] El Niños are thought to bring about an increase in some natural hazards on a nearly global scale by putting a greater amount of heat energy into the atmosphere. The heat energy in the atmosphere increases as more water evaporates from the ocean to the atmosphere. The increase of heat and water in the atmosphere produces more violent storms, such as hurricanes.

Figure 18.D shows the extent of natural disasters that have been attributed, in part, to the El Niño event of 1997–1998, when worldwide hurricanes, floods, landslides, droughts, and fires killed people and caused billions of dollars in damages to crops, ecosystems, and human structures. Australia, Indonesia, the Americas, and Africa were particularly hard hit. There is some disagreement about the amount of damage and loss of life directly attributable to El Niño, but few disagree about its significance.[42,43]

We do not yet completely understand the causes of El Niño events, which occur every few years, to a lesser or greater extent. Large El Niño events occurred in 1982–1983 and 1997–1998.

El Niño events can cause havoc by increasing the occurrence of hazardous natural events, and there is concern that human-induced climatic change may, through global warming, produce more and stronger El Niño events in the future. This effect would result, in part, because as we burn more fossil fuels and emit more greenhouse gases into the atmosphere, the oceans will continue to warm, and differential warming in various parts of the ocean may increase the frequency and intensity of El Niño events in the Pacific Ocean.

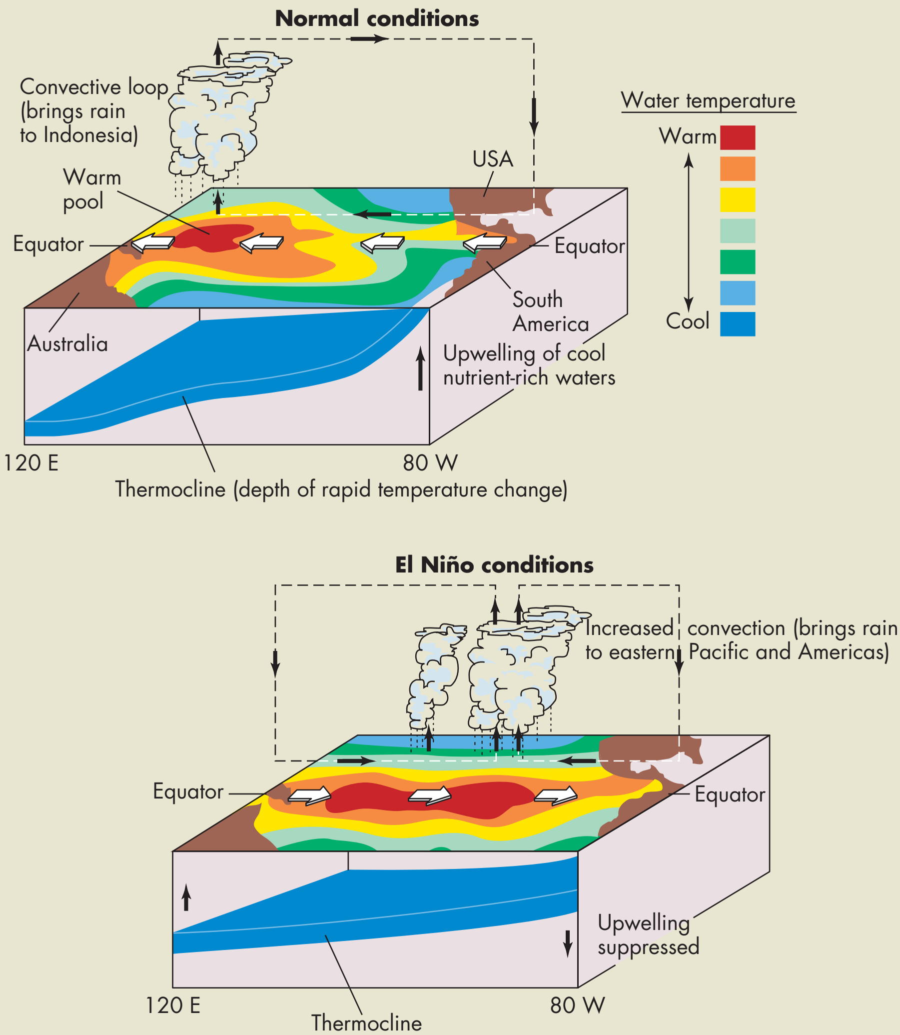


FIGURE 18.C El Niño Idealized diagram contrasting (a) normal conditions and processes with (b) those of El Niño. *(Modified after National Oceanic and Atmospheric Administration. www.elnino.noaa.gov. Accessed 3/3/99)*

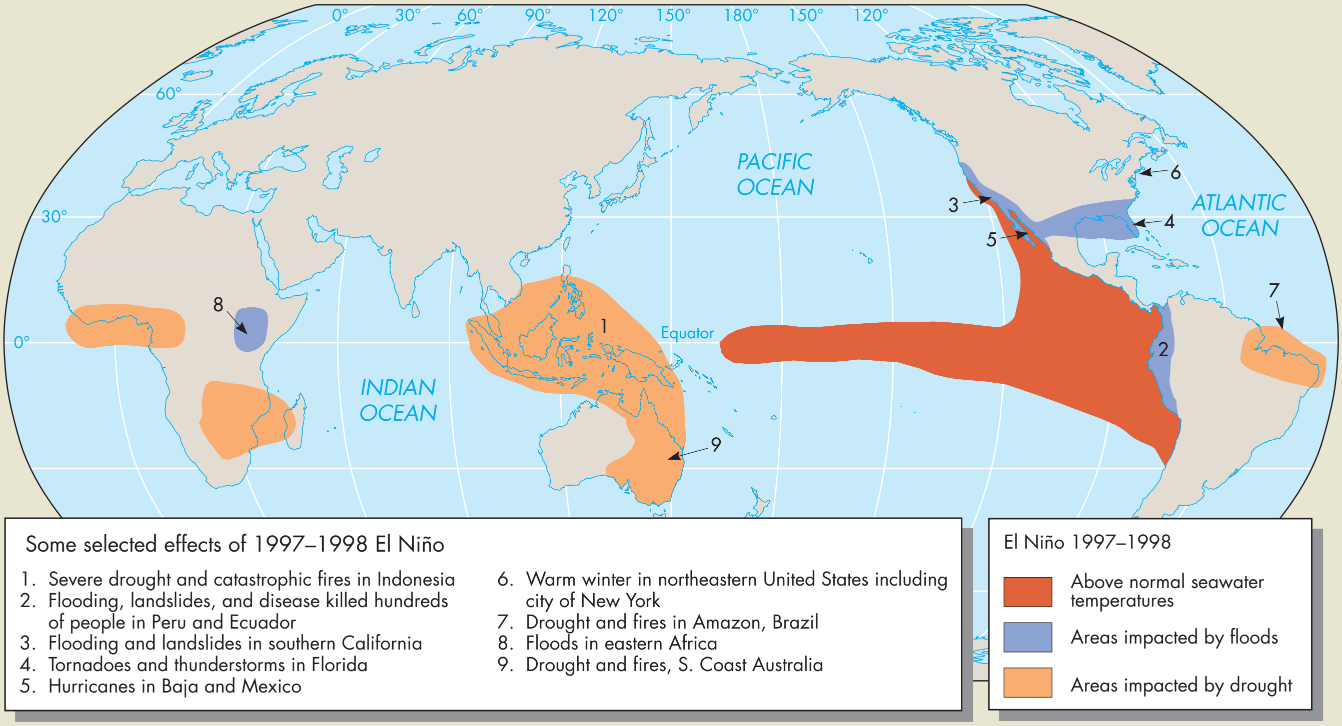


FIGURE 18.D The 1997–1998 El Niño event Map shows the general extent of the El Niño effects and the regions damaged by floods, fires, or drought. *(Data from National Oceanic and Atmospheric Administration, 1998)*

The opposite of El Niño is La Niña, in which eastern Pacific waters are cool. With La Niña events, droughts, rather than floods, may result in southern California. The alternation from El Niño to La Niña is a natural Earth cycle that has only recently been recognized.[44]

Estimates of the rise expected in the next century vary widely, from approximately 18 to 59 cm (7 to 23 in.), and precise estimates are not possible at this time. However, a 40 cm (16 in.) rise in sea level would have significant environmental impacts. Such a rise could cause increased coastal erosion on open beaches of up to 80 m (260 ft), rendering buildings and other structures more vulnerable to waves generated from high-magnitude storms. In areas with coastal estuaries, a 40 cm (16 in.) sea-level rise would cause a landward migration of existing estuaries, again putting pressure on human-built structures in the coastal zone. Communities would have to choose between making very substantial investments in controlling coastal erosion and allowing beaches and estuaries to migrate landward over wide areas.[7,45,46]

Rise in sea level is already threatening some small islands in the tropical Pacific Ocean. The island nation of Tuvalu consists of about nine atolls (**Figure 18.32**). As rising sea level since the last glacial maximum about 20,000 years ago overtopped a degraded carbonate platform, the atolls formed. The highest place on the island is only about 4.5 m (15 ft) above sea level. People first inhabited the island of Funafuti and other atolls of Tuvalu about 2,000 years ago, when stable inlets formed.[47] Recent sea-level rise is now threatening Funafuti, especially during high tides, which enhance wave attack and flooding. During high tide flood events (**Figure 18.33**), people report water bubbling up from the ground, contributing to the flooding of low-lying areas. With continued sea-level rise, the future ability of Funafuti and other

FIGURE 18.32 Funafuti, Tuvalu This atoll is part of the island nation of Tuvalu in the tropical Pacific Ocean, 3,000 km northeast of New Guinea. *(Global Warming Images/Alamy)*

FIGURE 18.33 Flooding of Funafuti Flooding of Funafuti, Tuvalu, during high tides in February 2005. *(Global Warming Images/Alamy)*

atolls to support people is uncertain. The 12,000 people on Funafuti could become the first to be displaced by rising sea level.

The northwestern and northern coastlines of Alaska are experiencing rapid erosion due to rise in sea level, melting permafrost soils, and loss of summer sea ice that can protect a coastline from erosion.[48] Some small islands may disappear, and some villages have already been moved inland.

Changes in the Biosphere

There is a growing body of evidence that global warming is initiating a number of changes in the biosphere, threatening both ecological systems and people. These include risk of extinction as land use changes and habitat becomes fragmented. Other changes include shifts in the range of plants and animals, with a variety of consequences: Mosquitoes carrying diseases, including malaria and dengue fever in Africa, South America, Central America, and Mexico, are migrating to higher elevations; butterfly species are moving northward in Europe; some bird species are moving northward in the United Kingdom; subalpine forests in the Cascade Mountains in Washington are migrating to higher meadows; alpine plants in Austria are shifting to higher elevations; sea ice melting in the arctic is placing stress on seabirds, walruses, and polar bears; and warming and increasing acidity of shallow water in the Florida Keys, Bermuda, Australia's Great Barrier Reef, and many other tropical ocean areas is believed to be contributing to the bleaching of coral reefs.[7,49,50]

Global warming is likely to affect many ecosystems in North America over the next 100 years because:[49]

- Warming is expected to be 2° to 4°C (3.6° to 7.2°F).
- Precipitation is projected to be less frequent but more intense.
- The temperature of streams and rivers will likely increase.
- Wildfires will be more frequent.
- Growing seasons will be lengthened, with earlier spring and greater primary productivity, especially at higher latitudes.
- Hurricane rainfall and wind speed are likely to increase.

As a result:

- Some ecosystems will experience stress.
- Many species may shift ranges north and toward higher altitudes in attempts to adapt to warming.
- Increases in disturbances may cause ecosystem changes to increase in time and space.

Changes are expected to affect marine ecosystems in a variety of ways. Approximately one-third of carbon dioxide emissions from human activities enter the oceans of the world. This decreases atmospheric concentration of carbon dioxide, reducing global warming, but at a cost to the oceans. Dissolved carbon dioxide and water form carbonic acid ($CO_2 + H_2O \rightarrow H_2CO_3$). The acid dissociates to bicarbonate ion (HCO_3^-) and hydrogen ion (H^+). As

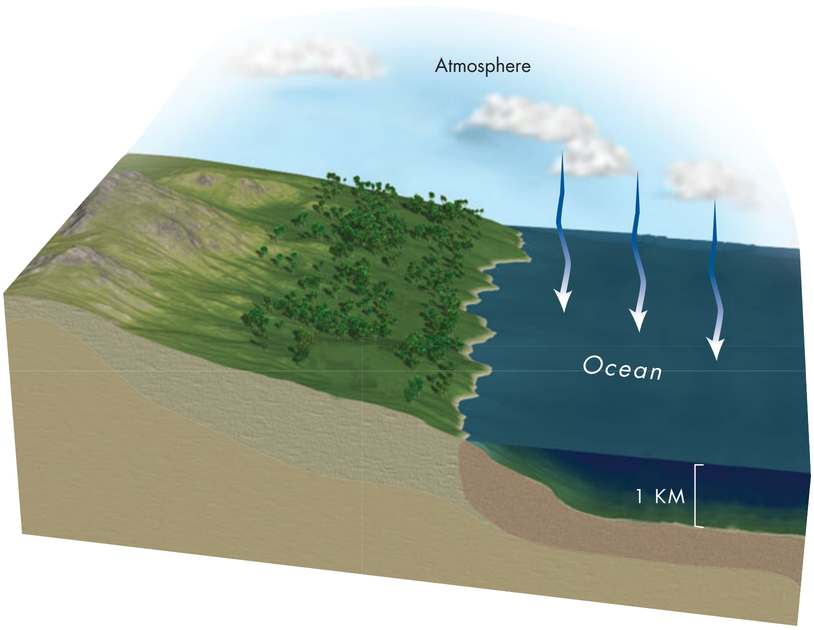


FIGURE 18.34 Changes in seawater Idealized diagram showing processes in shallow water less than about 1 km deep that changes the acidity of seawater.

H^+ increases, the water becomes more acidic (i.e., the pH of the water is reduced) (**Figure 18.34**). Over the past 15 years, ocean acidity has increased about 30 percent. The increased acidity of the ocean and ecosystem is fundamentally changing ocean chemistry structure and function by stressing marine organisms from plankton to coral and shellfish, as they attempt to adapt to increasing acidity. The stress for some species may be manifested in reduced growth rates and reproductivity. These changes will result because if organisms need to expend increased energy to maintain internal pH, they may have less energy for growth and reproduction. How individual species and ecosystems will respond to future increased acidification is a complex problem and is the subject of increased research.[51,52] Increased acidity of seawater may make it more difficult for some marine organisms that produce carbonate shells, such as oysters, coral, and some plankton, to draw carbonate from the seawater to make their shells.

In response to the warming atmosphere, ocean water temperature over the past 100 years has transferred heat to the upper water of the oceans. As a result, the average temperature of the upper 700 m of the sea has increased by about 0.6°C over the past century. Temperature increase has a fundamental effect on biological processes of marine organisms through increased metabolic rates, which impacts ecosystem processes of energy expenditure and chemical cycling. Marine organisms have the ability to adapt to temperature change within a range of temperatures at an optimal value. If the range is exceeded, the ability to adapt is reduced, and populations may decline or be driven to local extinction.[53] Mobile species such as fish can swim to other areas or deeper, where the temperature is closer to what they prefer. Those species tied to the bottom, such as shellfish, may slowly migrate if change is sufficiently slow. The changes of temperature and acidity of seawater appear to be accelerating, and that may make adaptation more difficult for some species.

Adaptation of Species to Global Warming

With global warming, regions of temperature and precipitation change, and this stresses ecosystems. During the past 25 years or so, plants and animals have shifted their ranges by about 6 km per decade toward the polar areas. In addition, spring is arriving earlier, and plants, as a consequence, are blooming earlier, frogs are breeding earlier, and migrating birds are arriving earlier in various places. The rate of change has been about 2.3 days per decade. In addition, it has been reported that tropical pathogens have moved up in latitude and elevation, affecting species that may

not be adapted to them. For example, in Costa Rica, more than 60 species of frogs may have gone extinct because of warmer temperatures that have affected their immune system response to a lethal fungus that has taken advantage of the warmer temperature. Climate change that warmed the air about 0.8°C may have caused the first extinction of a mammal, a species of white opossum that has apparently disappeared from Queensland, Australia. It was reported that the opossum lived only above an elevation of about 1,000 m and was very susceptible to being exposed to higher temperatures, even for a short period of time.[54]

A problem with past evaluations of a species potentially becoming threatened or even going extinct was that they were based on simple models that primarily considered temperature and precipitation, perhaps along with soil type and hydrology, that determine, in part, where species live. This information could then be put into a standard climate model to predict where a particular species might migrate in order to avoid adverse effects of climate change. We now know that these simple envelope models that use a few climate and topographic variables are not sufficient, and newer models that incorporate more biological elements, including competition among species and genetics, are being used to evaluate evolutionary response to climate change.[54,55]

A controversial suggestion is that we might assist migration of some species that are unable to migrate with climate change. To some, this is a drastic, controversial step that may be unacceptable due to the unanticipated risk of, essentially, creating an invasive species. Assisted migration worries ecologists and conservation biologists because they have spent a lot of time and effort working against invasive species, some of which cause ecosystem problems and the extinction of other species. Before we seriously consider assisted migration, much more research is needed to better understand the habitats of threatened and endangered species, including where they can do well, what might threaten them, and what they may threaten.[54]

Strategies for Reducing the Impact of Global Warming

Two big questions concerning the Earth climate system and people are (1) What changes have occurred and (2) What changes could occur in the future? Answering these questions requires geologic evaluation of prehistoric changes and the prediction, through modeling and simulation, of future change (**Figure 18.35**). Because we now know global warming is due in part to the increased concentration of greenhouse gases, reduction of these gases in the atmosphere is a primary management strategy. This was the subject of the 1997 United Nations Framework Convention on Climate Change in Kyoto, Japan. The objective of the convention was to produce an international agreement to reduce emissions of greenhouse gases, especially carbon dioxide. The United States originally agreed to reductions, but in 2001, it refused to honor the agreement, much to the disappointment of other nations, especially European allies. As a result, the leadership in controlling global warming has shifted from the United States to the European Union. The Kyoto Protocol was signed by 166 nations and became a formal international treaty in February 2005. The United States, as of 2010, had taken more active steps to deal with climate change through energy planning to reduce carbon emissions.

We face a dilemma with respect to burning fossil fuels. On one hand, fossil fuels are vital to our society and are necessary for continued economic

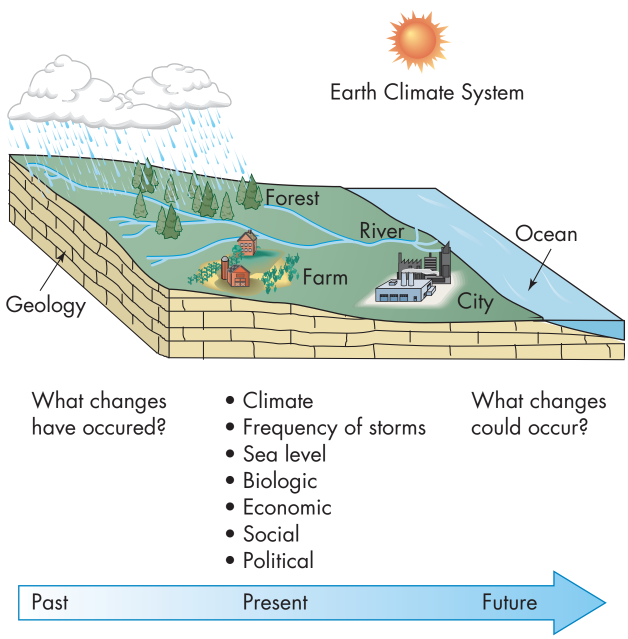


FIGURE 18.35 Two big questions concerning Earth's climate system These two questions are linked to people and the environment. *(Modified after International Panel on Climate Change, 2001, at www.ipcc.ch)*

development and growth, as well as human well-being. On the other hand, scientific evidence suggests that burning fossil fuels is contributing significantly to global warming. Burning fossil fuels is linked to environmental problems that include a rise in sea level, increased surface temperatures, and increased frequency and intensity of storms such as hurricanes. Impacts associated with fossil fuels depend upon how much the global temperature will actually rise. Estimates of temperature rise from climate models range from about 2° to 4°C.[7] If the increase is close to 2°C, we can probably adapt with minimal disturbance. If the increase in temperature is near the high end, significant impacts are likely. One way to estimate potential increase in temperature that is independent of the model predictions is to examine the geologic record for past change. A study of the geologic record from ocean sediments deposited during the past several hundred thousand years suggests that warming in the next century will be about 5°C, consistent with models that predict warming as great as 4.5°C.[56] If global temperature rises 4°C, than we will need a strategy to reduce emissions of carbon (about 50 percent over several decades) to avoid serious environmental disruptions that would result because, at this level of temperature increase, significant environmental impacts are much more likely. Also, it is important to recognize that, following the peak of emissions of carbon dioxide, it will probably take several hundred years or longer before temperature and sea level stabilize (**Figure 18.36**). Therefore, the sooner we act to reduce emissions, the lower the impacts will be and the sooner we will be on a path to stabilizing climate change. Even if carbon emissions were reduced to zero, warming will continue this century. There is 0.5° to 1.0°C additional warming in the Earth climate system now.

If reducing carbon emissions is necessary to reduce impacts of global warming, we need to take action. The reduction must occur at a time when human population and energy consumption are increasing. There are several ways that we might reduce emissions of carbon dioxide into the environment:

- Reduce emissions through improved engineering of fossil fuel–burning power plants (e.g., develop and use coal-burning power plants that sequester the carbon and place it in safe storage)
- Use fossil fuels that release less carbon into the atmosphere, such as natural gas, which, on burning, releases less carbon dioxide than does coal or oil (**Table 18.2**).
- Conserve energy to reduce our dependence on fossil fuels; use more alternative energy sources; and store carbon in Earth's systems such as forests, soils, and in rocks below the surface of Earth.[57–60]

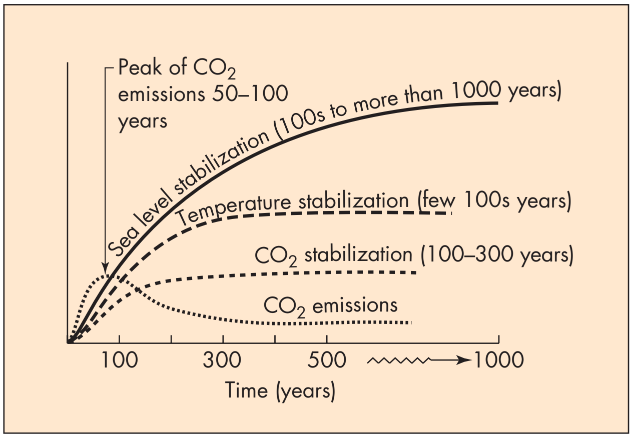


FIGURE 18.36 Lag times to stabilization of temperature, and sea level, following peak in emission. *(Modified after International Panel on Climate Change, 2001, at www.ipcc.ch)*

Storage of carbon in plants, soils, and the ocean has received considerable study. The option of sequestration of carbon in the geological or rock environment has received less attention. Sequestration is attractive because the residence time of carbon in the geologic environment is generally a long period of time, potentially thousands to hundreds of thousands of years.

The general principle of geologic sequestration of carbon is fairly straightforward. The idea is to capture carbon dioxide from power plants and industry and inject that carbon into the subsurface geologic environment. Two geologic environments have received considerable attention in this regard. The first is sedimentary rocks that contain salty water. These rocks, known as *saline aquifers*, are fairly widespread at numerous locations on Earth and have large reservoir capacity with the potential to sequester large amounts of carbon. Sedimentary rocks in these reservoirs have the potential to sequester many years of human-produced carbon dioxide emissions. They could provide the necessary time to transition to an energy economy not dependent on fossil fuels.[57] The second (but related) geologic environment for sequestration of carbon is

TABLE 18.2 Comparison of Common Fossil Fuels in Terms of Percentage of Total Carbon Released

Fossil Fuel	Carbon Emitted as Percentage of Total Carbon from Fossil Fuels (%)	Comparisons
Coal	36	Releases much more carbon per unit of energy than oil or gas.
Oil	43	Releases 23% less carbon per unit of energy than coal.
Natural gas	21	Releases 28% less carbon per unit of energy than oil or gas.

Data from Dunn, J. 2001. *Decarbonizing the Energy Economy.* World Watch Institute State of the World 2001. New York: W. W. Norton and Company.

depleted oil and gas fields. The process of placing carbon dioxide in the geologic environment involves compressing the gas to a mixture of both liquid and gases and then injecting it underground, using wells. Injecting carbon dioxide into depleted oil and gas fields has an added advantage: The carbon dioxide is not only stored but also serves to enhance recovery of remaining oil and gas in the reservoir by helping move the oil toward production wells.

A demonstration project is ongoing in Saskatchewan, Canada. The Weyburn oil field started production in the 1950s and was considered to be depleted. However, with enhanced recovery and storage of carbon dioxide, production is likely to last several more decades. The source of carbon dioxide for the Weyburn field comes from a coal-burning plant in North Dakota, by way of a pipeline that delivers several thousand tons of carbon per day.[57]

Another carbon sequestration project is located beneath the North Sea. Carbon dioxide is injected into a saltwater aquifer located below a natural gas field. The project, which started in 1996, injects about 1 million tons of carbon dioxide into the subsurface environment each year. It is estimated that the entire facility can hold about the amount of carbon dioxide that is projected to be produced from all of Europe's fossil fuel plants in the next few hundred years.[59] The cost of sequestering the carbon beneath the North Sea is expensive. However, it saves the company from paying carbon dioxide taxes for emissions into the atmosphere. Finally, pilot projects to demonstrate the potential and usefulness of storing carbon in the United States have been initiated in Texas, beneath depleted oil fields. The good news is that immense salt aquifers are common beneath many areas of the United States, including the Gulf Coast, Texas, and Louisiana, and the potential to store carbon is immense.[59]

Recent studies suggest that global warming is probably not an immediate emergency, and we will have a decade or so to develop alternatives to continued intensive burning of fossil fuels. If we decide that we must stabilize the concentration of atmospheric carbon dioxide in the future, it will be necessary to go through a transition from fossil fuel energy sources to alternative sources that produce much less carbon dioxide. However, speculation based on studies of glacial ice cores from Greenland indicates that significant climatic change may occur quickly, perhaps in as little as a few years. A quick natural or human-induced warming or cooling is probably unlikely, but if one does occur, the potential impacts could be fast and serious (see A Closer Look: Abrupt Climate Change). Human civilization began and has developed into our present highly industrialized society in only about 7,000 years. That period has been characterized by a relatively stable, warm climate that is probably not characteristic of longer periods of Earth history. It is difficult to imagine the human suffering that might result late in the twenty-first century from a quick climate change to harsher conditions, when there are as many as 10 billion or more people on Earth to feed.[17]

18.7 Coupling of Global Change Processes: Ozone Depletion and Global Warming

The major global change processes discussed in this chapter have important linkages. For example, the chlorofluorocarbons (CFCs) that cause ozone (O_3, triatomic oxygen) depletion when they reach the stratosphere also contribute to the greenhouse effect when they are released into the lower atmosphere.

A Closer Look

Abrupt Climate Change

Abrupt climate change is defined as a large-scale change in the global climate system that takes place over a few decades or less. Such change is anticipated to persist for at least a few decades and will cause substantial disruptions to both human and natural systems.[61] Several types of abrupt climate change could cause serious risk to humans and the natural environment in terms of our ability to adapt, including:

- A rapid change of sea level as a result of changes in the glaciers and ice sheets
- Droughts and floods, resulting from widespread rapid changes to the hydrologic cycle
- Abrupt change in the pattern of circulation of water in the Atlantic Ocean that is characterized by northward flow of warm, salty water in the upper layers of the ocean
- A rapid release of methane (a strong greenhouse gas) to the atmosphere from both thawing permafrost and the ocean's sediment

These four potential abrupt changes have been addressed by the U.S. Climate Change Science Program.[61]

One of the major questions is whether there will be abrupt changes in sea level. We know that even small changes in sea-level rise may have significant repercussions for society, with serious economic impacts, including coastal erosion as well as an increase in coastal flooding and a loss of coastal wetlands. The present climate models do not adequately capture all aspects of sea-level changes resulting from melting glacial ice. However, given this, there is a concern that projections for sea-level rise in the future, as presented by the Intergovernmental Panel on Climate Change,[7] probably underestimate the amount of sea-level rise during the twenty-first century.

A second question involves the potential for abrupt changes of the hydrologic cycle. Of particular concern are changes that affect water supply, particularly through long, protracted droughts. Of particular significance is the fact that droughts can develop faster than people and society are able to adapt to them. Thus, droughts that last from several years to a decade or more have serious consequences to society. It has been pointed out that long droughts have occurred in the past and are still likely to occur in the future, even in the absence of global warming, as a result of increased greenhouse-gas forcing.[61]

A third question concerning abrupt change has to do with the Atlantic Ocean circulation system, which carries warm water to the North Atlantic, where it becomes saltier and sinks to become a cold water bottom current that moves south. The warm water is partly responsible for keeping Western Europe comfortable and hospitable. However, it is primarily the large expanse of the ocean itself that accomplishes this. The strength of this current is expected to decrease approximately 25 to 30 percent as a result of the global warming in the twenty-first century. However, it appears very unlikely that the ocean current system in the Atlantic will undergo a collapse or an abrupt transition to a very weakened state in the next 100 years.[61]

A final question concerning abrupt change is whether there will be a rapid change in atmospheric methane. This is a significant question because methane is a strong greenhouse gas that, if greatly increased in concentration in the atmosphere, would accelerate global warming. It is generally concluded that a very rapid change in the release of methane during the next 100 years or so is very unlikely. However, ongoing warming will increase emissions of methane from both ocean sediments and wetlands. Wetlands in the northern high latitudes are particularly more susceptible to releasing additional methane because there is accelerated warming, along with enhanced precipitation, in permafrost areas that contain a lot of stored methane. Thus, it appears that, in future decades, methane levels will likely increase and cause additional warming.[61]

In conclusion, it appears that abrupt climate change during the next century is unlikely, and, thus, we will most likely have time to respond to potential adverse consequences of global warming. However, it takes time to initiate change in policy, and time is growing short; a serious response to global warming from all countries is necessary in the near future.

A better understanding of past abrupt changes in climate, through the collection and analysis of geologic data, is necessary to fully understand what may cause future change. Geologic data provide the most direct evidence of past change. Geologic data from sediments and glacial ice, along with monitoring, are assisting in understanding the causes of long-term changes in ocean and glacial conditions and how these are linked to atmospheric response. With this, we may be better able to forecast both long- and short-term droughts that have serious consequences to humans and the natural environment.

The processes responsible for stratospheric **ozone depletion** and development of the Antarctic ozone hole are complex but related to chemical reactions between chlorine (Cl) and ozone (O_3), linked to the Antarctic polar vortex (where there is counterclockwise rotation of the atmosphere), and polar stratospheric clouds where ozone-depleting reactions happen. The air mass in the vortex is isolated, cools, condenses, and descends.[62] Chlorofluorocarbons, which contain chlorine, are stable in the lower atmosphere but wander up to the stratosphere. There, chlorine is split from CFCs by ultraviolet radiation from the Sun and reacts with ozone to produce chlorine oxide and oxygen: $Cl + O_3 \rightarrow ClO + O_2$. The result is destruction of the ozone. The chlorine is released from chlorine oxide (ClO) by a subsequent reaction with monoatomic oxygen (O): $ClO + O \rightarrow Cl + O_2$, releasing Cl to destroy more ozone by the first reaction (**Figure 18.37**). The reactions are complex but follow the general equations just mentioned. The two important sinks for chlorine in the clouds are hydrochloric acid (HCl) and chlorine nitrate. With denitrification, chlorine (Cl_2) is released to enter into ozone-depletion reactions (see Figure 18.37). During the Antarctic spring, these chain reactions may happen very quickly, causing up to 2 percent ozone depletion each day and, ultimately, producing the observed 50 to 70 percent annual depletion. In the lower atmosphere, where they are emitted, CFCs trap more heat than carbon dioxide because they can absorb more infrared radiation. One study concluded that, on a per-molecule basis, chlorofluorocarbons are several thousand times more efficient at absorbing infrared radiation than is carbon dioxide. Nevertheless, carbon dioxide contributes much more to the total anthropogenic

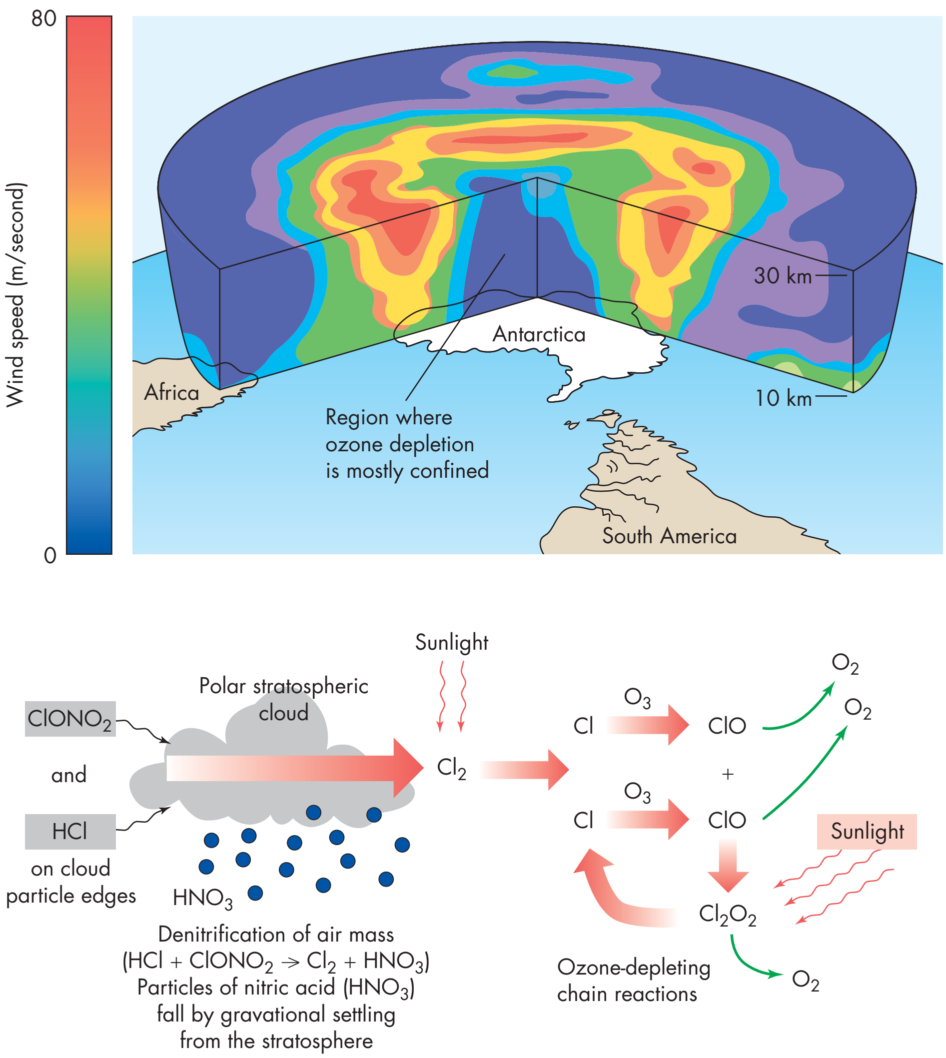


FIGURE 18.37 Antarctic polar vortex Idealized diagrams of the Antarctic polar vortex and the role of polar stratospheric clouds in the ozone depletion chain reaction. *(Based on Toon, O. B., and Turco, R. P. 1991. Polar stratospheric clouds and ozone depletion.* Scientific American *264(6):68–74)*

greenhouse effect than do CFCs because so much more carbon dioxide is being emitted.[63]

The coupling of the greenhouse and ozone problems via release of materials such as CFCs is an important point to consider. Other couplings, related to processes such as the burning of fossil fuels, release precursors to acid rain as well as carbon dioxide and other greenhouse gases (see Chapter 16). Burning fossil fuels and volcanic eruptions, as discussed earlier, also produce particulates that result in atmospheric cooling. Carbon dioxide has the predominant effect on changing global temperature, but we see the principle of environmental unity in action. Many aspects of one problem, in this case global warming, are related to other processes or problems, such as ozone depletion.

Making The Connection

Linking the Opening Case History About the MWP and LIA to the Fundamental Concepts

Consider and discuss the following questions:

1. Why are climate change and the MWP important to how we think about sustainability and climate change today?
2. What can we learn about the MWP that could influence our thinking about climate change in the twenty-first century?
3. Does the study of past climate change during the MWP and the more recent Little Ice Age have significance with respect to understanding of and response to natural hazards related to climate change? How?
4. How do science and values link to our energy choices related to potential global warming in the twenty-first century?

Summary

The main goal of the emerging integrated field of study known as Earth systems science is to obtain a basic understanding of how our planet works and how its various components, such as the atmosphere, oceans, and solid Earth, interact. Another important goal is to predict global changes that are likely to occur within the next several decades. The global changes involved include temperature, or climate, changes and the resulting changes in seawater and on land. Because these are short-term predictions, Earth systems science is relevant to people everywhere.

Methods of studying global change include examination of the geologic record from lake sediments, glacial ice, and other Earth materials; gathering of real-time data from monitoring stations; and development of mathematical models to predict change. Sources of data that are used in the study of climate change include measurements from the instrumental record; the historic record; and climate proxy data such as study of tree rings and measurement of carbon dioxide and methane from ice bubbles in glaciers.

Climate refers to characteristic atmospheric conditions, such as precipitation and temperature over seasons, years, and decades. The atmosphere is a dynamic, complex environment where many important chemical reactions occur.

Human activity is contributing significantly to global warming. The trapping of heat by the atmosphere is referred to as the greenhouse effect. Water vapor and several other gases, including carbon dioxide, methane, and chlorofluorocarbons, tend to trap heat and warm Earth because they absorb some of the heat energy radiating from Earth. The effects of a global rise in temperature include a rise in global sea level and changes in rainfall patterns, high-magnitude storms, soil moisture, agriculture, and the biosphere.

Natural climate-forcing mechanisms that may cause climatic change include Milankovitch cycles, solar variability, and volcanic activity. Anthropogenic causes include air pollution and increases in greenhouse gases, especially carbon dioxide. We now understand that global

climate can change rapidly over a time period of a few decades to a few hundred years. Two important questions are: What changes have occurred and What changes could occur in the future?

The science of global warming is well understood. Human-induced global warming is occurring. There is no reason for gloom and doom, but we need to take appropriate action soon to slow or stop global warming and associated environmental consequences.

Adjustments to global warming will vary, from adapting to change, to reducing emissions of carbon dioxide, to sequestration of carbon. Several different simultaneous adjustments are likely.

Some global changes, such as ozone depletion and the greenhouse effect, are coupled. For example, the CFCs released in the lower atmosphere add to the greenhouse effect before diffusing to the stratosphere, where they cause ozone depletion.

Revisiting Fundamental Concepts

Human Population Growth Increase in human population is one of the driving forces of the human-induced component of global warming. The United States, with about 5 percent of the world's population, emits about 20 percent of the carbon dioxide, thought to contribute to warming through the greenhouse effect. As population continues to increase beyond the 7 billion today toward 8 to 9 billion by 2050, restructuring energy uses and sources will be necessary to minimize global warming.

Sustainability A relatively stable global climate is desired and necessary for future generations of people and is also necessary for healthy ecosystems. Rapid or dramatic warming or cooling of the climate would be difficult for society to adjust to. Presently, our energy policies of burning vast amounts of fossil fuels are not sustainable. If we continue to emit huge amounts of greenhouse gases, we will continue to perform an unplanned global experiment with untested but predictable adverse consequences.

Earth as a System Earth is a planetary system—with linkages between air, water, soil, rock, and living things—that changes in many ways. Understanding the Earth system and how it changes is important if we are to solve environmental problems such as climate change and associated global warming.

Hazardous Earth Processes, Risk Assessment, and Perception Global warming is linked to a variety of natural hazards, including flooding, severe storms, and coastal erosion. The changes in risks and resulting damages from natural hazards that are likely to occur as the atmosphere warms are being studied. Our perception of hazards will change as the frequency and intensity of events increase or decrease in the future.

Scientific Knowledge and Values Scientific understanding of global change and climate change has improved greatly in the past few years. Although details are sketchy, we have a good idea of the potential adverse consequences of our present energy policy of burning fossil fuels. Our values are being tested as never before. Reducing emissions of carbon dioxide will require a new energy policy that some fear will cause financial damage to our economy. Others believe the transition to alternative energy sources that do not pollute the environment or cause climate change and associated global warming will be difficult but is absolutely necessary. Regardless of their position on energy sources, people place a high value on living in a pollution-free environment without the threat of rapid, potentially damaging climate change.

Key Terms

climate (p. 623)
climate forcing (p. 634)
desertification (p. 647)
Earth climate system (p. 622)
Earth systems science (p. 619)
El Niño (p. 646)
glacier (p. 638)
global dimming (p. 638)
global warming (p. 630)
greenhouse effect (p. 626)
ozone depletion (p. 658)
proxy data (p. 627)

Review Questions

1. What are the two central goals of Earth science, as defined by Preston Cloud?
2. Define *Earth systems science*.
3. What are the major tools and methods for studying global change?
4. Define *climate*.
5. Define *glacier*.
6. What is desertification?
7. What are the three main factors that determine the temperature of Earth?
8. Why do we think that the late twentieth-century global warming is due to human activity?
9. What is the greenhouse effect?
10. Why is the so-called ocean conveyer belt important?
11. What are the major potential effects of global warming?
12. What are the main ways to reduce emissions of carbon dioxide?
13. Why are CFCs thought to be responsible for the destruction of ozone in the stratosphere?
14. How are CFCs and carbon dioxide both involved in potential global warming?

Critical Thinking Questions

1. Have a discussion with your parents or someone of similar age and write down the major changes that have occurred in their lifetime as well as yours. Characterize these changes as gradual, abrupt, surprising, chaotic, or using another description of your choice. Analyze these changes and discuss which ones were most important to you personally. Which of these affected our environment at the local, regional, or global level?
2. How do you think future climate change is likely to affect you, particularly considering the environmental problems we may be facing as a result of increased world population?
3. Do you think that we need additional studies to further confirm that human activity is a significant component of the late twentieth-century warming before taking steps to reduce potential adverse impacts? Why? Why not?
4. Do you think that global warming from increasing CO_2 might be saving us from another glacial period? What is the role of global dimming in this question?

Companion Website

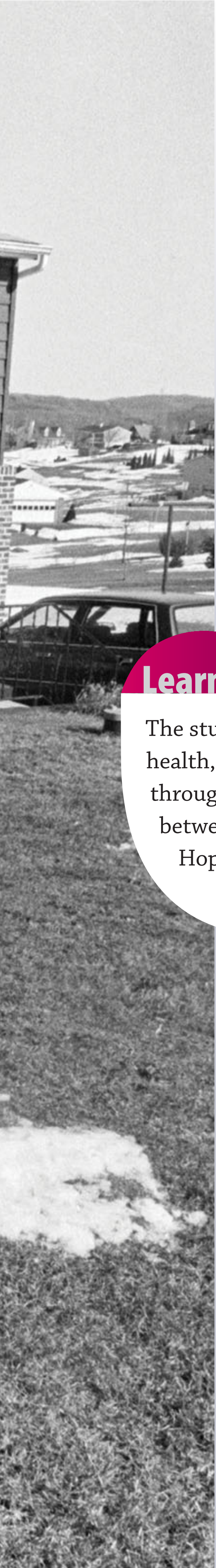
www.mygeoscienceplace.com

PEARSON mygeoscience place™

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Stanley Watras family home This home (in 1984) in Boyertown, Pennsylvania, had extremely high naturally occurring levels of radon gas in 1984 before being remediated. *(Bettmann/Corbis)*



19 Geology, Society, and the Future

Learning Objectives

The study of geology and its relationship to specific functions of society, such as environmental health, environmental impact, and land-use planning, relies on integrating what we have learned throughout this book. In this sense, this chapter is a capstone. At a deeper level, relationships between people and our environment provide insight into why we study environmental geology. Hopefully, we will build on past successes and learn from our mistakes. In this chapter, we will focus on the following learning objectives:

- **Understand geologic aspects of environmental health, air pollution, and waste management**
- **Understand the geologist's role in evaluating land for appropriate uses**
- **Understand environmental impact analysis, including the major components of an environmental impact statement and the processes of scoping and mitigation**
- **Know the processes of law, particularly the use of mediation and negotiation to resolve environmental conflicts**
- **Know the three steps we can take to avert a potential environmental crisis, with potential loss of food supply, caused by the convergence of human population increase, reduction in water resources, and global warming**
- **Be able to discuss what steps are necessary to attain the goal of sustainability**

Case History

Radon Gas: The Stanley Watras Story

In December 1984, scientists discovered that radon (a radioactive gas) from natural sources (i.e., soil and rock) may enter the home and possibly present a serious health hazard. The story of Stanley Watras has been told and retold many times, until it is now part of radon legend.[1] Nevertheless, it is worth repeating here. Stanley Watras lived in Boyertown, Pennsylvania, and, in December 1984, had a job as technical advisor in the Limerick nuclear power station. At the entrance to the plant are radiation detectors to ensure that no radioactive materials leave the facility. The reactor at the power plant had not yet been turned on when Watras, on his way into the plant, set off the alarms! Testing of his clothing suggested that the contamination could not have come from the plant but must have come from where he lived. Power company officials checking Watras's home were astounded to find that the radiation level of the indoor air was 3,200 pCi/L. Scientists were very surprised because, until then, they had not believed that radon that naturally seeped into homes could be hazardous to anyone. The level of 3,200 pCi/L is 800 times higher than the level of 4 pCi/L, considered as a threshold for hazard by the U.S. Environmental Protection Agency. The Watras home held the record for indoor radon concentration until the latter part of the 1980s, when a home in Whispering Hills, New Jersey, was discovered to have a radiation level of 3,500 pCi/L.[2]

The Watras family moved from the home, and, through mitigation measures (e.g., sealing leaks and ventilation), the radon level of the home was reduced to a safe level. The Watras family then moved back into the home. It is reported that Stanley started a firm that evaluated and mitigated radon in buildings, and that the new work was a therapeutic experience linked to his personal experience with radon.

Since 1985, awareness of the radon gas problem in the United States has increased. Nevertheless, people have a hard time focusing on a problem that they can't see, smell, hear, or touch. The problem is further compounded by the fact that some property owners seem to be more concerned about potential loss of property values than the health hazard. There is a considerable gap between people's perception of the radon problem and the potential size of the problem itself.

The radon problem is a good example of how geology may be linked to society. The gas is natural, so we can't blame people, economics, or politics for the health hazard it produces. Fortunately, radon is a hazard with a relatively easy fix. In this chapter, we will discuss several ways geology interacts with society:

- Environmental health (including radon gas)
- Air pollution
- Waste management and environmental law
- Site selection
- Environmental impact analysis
- Land use planning

19.1 Introduction

We live on the surface of Earth, which has developed landforms, such as mountains, plains, river valleys, hill slopes, and shorelines, through the interactions of many geologic and biogeologic processes. In most places, a biogeologic layer of Earth material that we call *soil* covers the surface. Ever since people began gathering in villages that became cities, practicing agriculture, and manufacturing products from a variety of Earth materials, geology has played an important role in society. In other parts of this book, we discussed some of the major Earth processes, including natural hazards, and resources, such as minerals, water, and soil, and their interactions with human behavior and processes. In this chapter, we will further examine examples of relationships between geology and the needs of society. We will begin with environmental health.

19.2 Geology and Environmental Health

As members of the biological community, humans have carved a niche in the biosphere—a niche that is highly dependent on complex interrelations among the biosphere, atmosphere, hydrosphere, and

lithosphere. Yet, we are only beginning to inquire into and gain a basic understanding of the total range of environmental factors that affect our health and well-being. As we continue our exploration of the geologic cycle—from minute quantities of elements in soil, rocks, and water to regional patterns of climate, geology, and topography—we are making important discoveries about how these factors may influence death rates and incidences of certain diseases. In the United States alone, the death rate varies significantly from one area to another,[3,4] and some of the variability results from the local, physical, biological, and chemical environment in which we live (see A Closer Look: Lead in the Environment).

At this point, it is useful to introduce a few basic terms and definitions. For example, **toxicology** is the science involved in the study of poisons, or *toxins*, and their potential effects on people and ecosystems, as well as clinical, economic, industrial, and legal problems associated with toxic materials in the environment. A special type of toxin that causes cancer is called a *carcinogen*; carcinogens are some of the most feared and heavily regulated toxins in society today. The concentration of a particular toxin or carcinogen is often reported in units such as parts per million (ppm) or parts per billion (ppb). These are incredibly small numbers. For example, perhaps you are making popcorn and would like to add some salt to it. Using your standard 737 g (1 lb 10 oz) container of iodized salt, you want to season the popcorn at a concentration of 1 ppm. To set that concentration, using the whole container of salt, you would have to pop approximately 737 metric tons of kernels of corn, more than 6 million quarter-pound bags of popcorn! The average person has a hard time understanding that such small concentrations as parts per million or parts per billion of a chemical can cause cancer or be toxic. Finally, toxins and other pollutants in the atmosphere are usually measured as micrograms per liter (μg/L) or micrograms per cubic meter ($\mu g/m^3$) of air. Radioactive radon in air is an exception; radon gas is reported in picoCuries per liter (pCi/L), a reference to the number of radioactive disintegrations per second in a liter of air.

Disease has been described, from an environmental perspective, as an imbalance resulting from a poor adjustment between an individual and the environment.[9] It seldom has a single cause. The geologist's contribution to our understanding of its causes helps isolate aspects of the geologic environment that may influence the incidence of disease. This tremendously complex task requires sound scientific inquiry, coupled with interdisciplinary research with physicians and other scientists. Although the picture is now rather vague, the possible rewards of the developing field of medical geology are exciting and are contributing in many ways to the understanding of environmental health.

Some Geologic Factors of Environmental Health

The soil in which we cultivate plants for food, the rock on which we build our homes and industries, the water we drink, and the air we breathe all influence our chances of developing serious health problems. Conversely, these factors can also influence our chances of living longer, more productive lives. Surprisingly, many people still believe that soil, water, or air in a "natural," "pure," or "virgin" state must be "good," and that, if human activities have changed or modified these resources, they have become "contaminated" or "polluted" and, therefore, "bad." This simple dichotomy is by no means the entire story.[9–11]

Chronic Disease and the Geologic Environment

Health can be defined as an organism's state of adjustment to its own internal environment and to its external environment. Observation over many years has suggested that some regional and local variations in human chronic diseases, such as cancer and heart disease, are related to the geologic environment. Although evidence continues to accumulate and medical geology is a rapidly growing field, the exact nature of many associations remains to be discovered. There are three main reasons for the lack of conclusive results: (1) Hypotheses generated about relationships between the geologic environment and disease have not usually been specific enough to be tested adequately to make predictions beyond comparison between geochemical data and incidence of disease; (2) there are many methodological difficulties in obtaining reliable and comparable data for medical–geological studies; and (3) there are significant problems with geographical variability in disease.[4] We know much less about geologic (i.e., biogeochemical) influences on chronic disease than about the contribution of other environmental factors, such as climate.

Although our evaluation of geologic contributions to disease in some cases remains an educated guess,

A Closer Look: Lead in the Environment

The incidence of lead poisoning is an example of geologic, cultural, political, and economic influences on patterns of disease. The effects of lead poisoning can include anemia, mental retardation, and palsy. For decades, lead was used in gasoline, resulting in polluted soil near highways. Until recently, lead was also used in many other products, including paints. Some children chewing on these painted surfaces ingested lead in toxic amounts. Lead is also found in some moonshine whiskey and has resulted in lead poisoning among adults and even unborn or nursing infants whose mothers drank it.[5]

It has been suggested that widespread lead poisoning was one of the reasons for the fall of the Roman Empire. Some historians estimate that the Romans produced about 55,000 metric tons of lead each year for several hundred years. The Romans used lead for pots, for wine cups, and in cosmetics and medicines. The ruling class also had water running through lead pipes into their homes. Historians argue that gradual lead poisoning among the upper class resulted in their eventual demise through widespread stillbirths, deformities, and brain damage. The high lead content found in the bones of ancient Romans lends support to this hypothesis.[6] Further support of this theory comes from a study of ice cores from Greenland's glaciers; for the period 600 B.C. to A.D. 300 (time of the Roman Empire), lead concentrations in the ice are significantly higher than before the Roman Empire. This finding suggests that lead mining and smelting during the Roman Empire caused lead contamination in the atmosphere over the Northern Hemisphere.[7]

We have known for a long time that, at high concentrations, lead is an extremely toxic metal that causes serious health problems. More recently, it has been suggested that lead in urban areas can also cause social problems. In one study, children with above-average lead concentrations in their bones were found to be more likely to have attention-deficit disorder or delinquency problems and to exhibit aggressive behavior than were children with lower lead concentrations.[8] On the basis of this finding, some part of the crime rate and aggressive behavior of children in urban areas may be attributed to environmental pollution, as well as to socioeconomic conditions. If environmental pollution does contribute to social problems, then how we manage urban environments is enormously significant. The idea that aggressive behavior is due, in part, to our contaminated environment is controversial, and additional studies are necessary to verify these conclusions.

the benefit of learning more about these relationships is obvious. The geographic variations in the incidence of heart disease in the United States may be related to the geologic environment. In addition, many forms of cancer result, in part, from environmental causes (e.g., exposure to chemicals), and genetic factors are also important.

Heart Disease and the Geochemical Environment

Our use of the term *heart disease* here includes coronary heart disease (CHD) and cardiovascular disease (CVD). Variations in heart disease mortality have generally shown interesting relationships with the chemistry of drinking water—in particular, with the hardness of drinking water. Hardness is a function of the amount of calcium, magnesium, and iron that is dissolved in water. Higher concentrations of these elements produce harder water. Water with low concentrations of these elements is termed *soft*. Studies in Japan, England, Wales, Sweden, and the United States all conclude that communities with relatively soft water have a higher rate of heart disease than do communities with harder water.

Perhaps the first report of a relationship between water chemistry and cardiovascular disease came from Japan, where a prevalent cause of death is stroke, a sudden loss of body functions caused by the rupture or blockage of a blood vessel in the brain. The geographic variation of the disease in Japan is related to the relative softness or hardness of river water. **Figure 19.1** shows that areas in

Japan with high death rates due to stroke generally correspond to areas of relatively soft water.[12]

The relatively soft water of the northeastern part of Japan evidently stems from the sulfur-rich volcanic rock found in that region. Rivers in the region have relatively soft water. Rivers in Japan that flow through sedimentary rocks have, in contrast, relatively hard water, as do most other rivers in the world.

A general inverse relationship between hard water and death rates from heart disease is also present in the United States.[13,14] For example, similarly to the Japanese report, a study in Ohio suggests that hard water may influence the incidence of heart disease.[15] The Ohio study found that counties with relatively soft drinking water, derived from coal-bearing rocks in the southeastern part of the state, tend to have a higher death rate due to heart attack than do counties with relatively hard drinking water, derived from young glacial deposits (**Figure 19.2**). It is important to realize, however, that this generally negative correlation is not conclusive. A study in Indiana found a small positive correlation between heart disease and

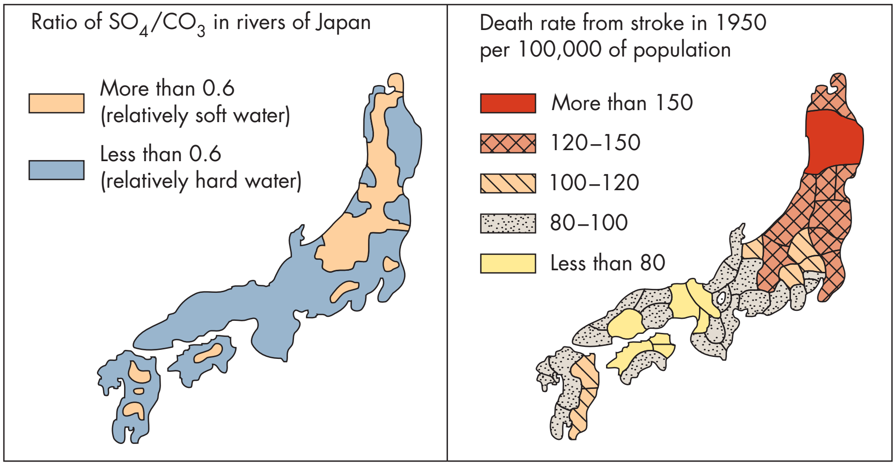


FIGURE 19.1 Stroke Maps of Japan comparing relatively soft and hard water in rivers with the death rate from strokes in 1950. *(Data from T. Kobayashi, 1957)*

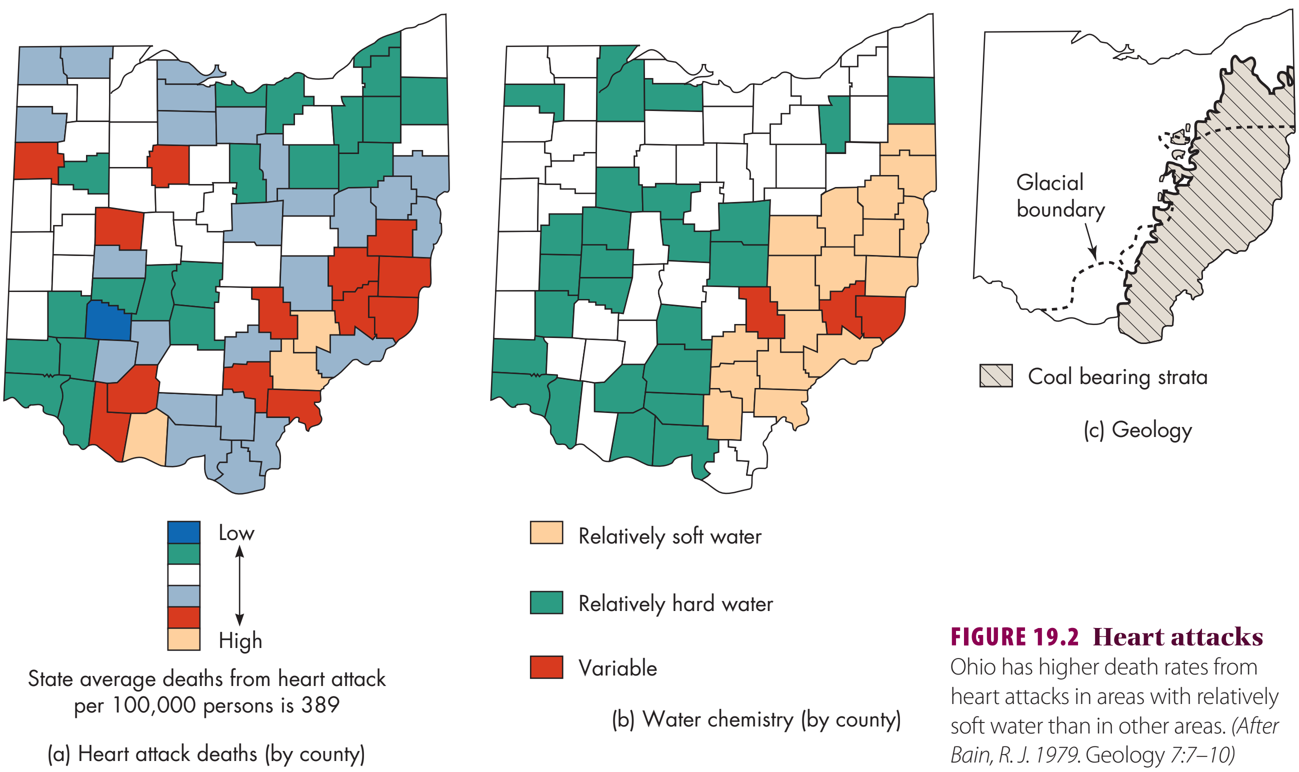


FIGURE 19.2 Heart attacks Ohio has higher death rates from heart attacks in areas with relatively soft water than in other areas. *(After Bain, R. J. 1979. Geology 7:7–10)*

hardness of water, suggesting that many other variables may exert considerable influence on rates of heart disease.[16]

The correlations discussed do not necessarily show a cause-and-effect relationship between the geochemical environment and heart disease. If there is a cause-and-effect relationship, we do not know its nature, but there are several possibilities:

- Soft water is more acidic than hard water and may, through corrosion of pipes, release into the water trace elements that cause heart disease.
- Some other characteristics of soft water may contribute directly to heart disease.
- Some substances dissolved in hard water may help prevent heart disease.

Of course, some combination of these and other factors is also possible and is consistent with our observation that a disease may have several causes. Additional research is needed to prove the benefit of hard water and to, perhaps, suggest treatment of soft water to reduce heart disease.

Cancer and the Geochemical Environment

Cancer tends to be strongly related to environmental conditions. However, as is the case for heart disease, relationships between the geochemical environment and cancer have not been proved. The causes of the various types of cancers are undoubtedly complex and involve many variables, some of which may be the presence or absence of certain Earth materials.

Cancer-causing, or *carcinogenic*, substances in the environment have two origins: Some occur naturally in Earth materials, such as soil and water; others are released into the environment by human use. In recent years, attention has been focused on the many known and suspected carcinogens released by human industrial activities. This awareness has sometimes resulted in alarm concerning substances whose relationship to cancer is not well demonstrated. This does not mean that all concern about industrial carcinogens is misplaced. Recent information suggests that variable concentrations of cancer-causing substances may be found in much of our drinking water. Carcinogens may or may not be in our drinking water, but, certainly, water polluted with industrial waste containing toxic chemicals, some of them possible carcinogens, is being released into our surficial water supplies. The Mississippi River, particularly, has pollution problems. Ironically, present methods of water treatment that use chlorine may contribute to these problems: When combined with chlorine, some industrial waste turns into cancer-producing material. In addition, antiquated water-treatment procedures in some areas fail to remove certain carcinogens. Naturally occurring airborne carcinogenic substances are also found in some of our homes and buildings (see A Closer Look: Radon Gas).

19.3 Air Pollution: Introduction and Geologic Perspective

As the fastest-moving dynamic medium in the environment, the atmosphere has always been one of the most convenient places for people to dispose of unwanted materials. Ever since humans first used fire, the atmosphere has, all too often, been a sink for waste disposal. With the rapid urbanization and industrialization of the past two centuries, atmospheric circulation has often proved inadequate to dissipate human wastes, and urban air, in particular, has become increasingly polluted.

Chemical pollutants can be thought of as compounds that are either in the wrong place or in the wrong concentrations at the wrong time. As long as a chemical is transported away or degraded rapidly relative to its rate of production, there is no pollution problem. Pollutants that enter the atmosphere through natural or artificial emissions may be degraded by natural processes within the atmosphere, as well as by the hydrologic and geochemical cycles. Conversely, pollutants in the atmosphere may become pollutants in the hydrologic and geochemical cycles (as, for example, acid rain; see Chapter 16).

Today, air pollution is a well-known, serious health hazard in many large cities. For example, in Los Angeles, California, millions of people are regularly exposed to unhealthy air. Although Los Angeles has the country's most serious air pollution problem, it is only one of many U.S. cities with unhealthy air. Other U.S. cities with serious air pollution problems include Houston, Texas; Baltimore, Maryland; Charlotte, North Carolina; and Atlanta, Georgia. With the minor exception of the Pacific Northwest, no U.S. region is free from air pollution.[27] Approximately

A Closer Look

Radon Gas

Radon gas is a significant source of indoor air pollution with strong links to geology (see case history opening this chapter). **Radon** is a naturally occurring radioactive gas that is colorless, odorless, and tasteless. Uranium-bearing rocks are the source of the radon gas that contaminates many homes in the United States.

Exposure to elevated concentrations of radon is associated with increased risk of lung cancer, particularly for smokers. The risk is thought to increase as the level of radon concentration, the length of exposure to radon, and the amount of smoking increase.[17,18]

In recent years, there have been approximately 140,000 lung cancer deaths each year in the United States. Although smoking is the most important factor associated with lung cancer, the Environmental Protection Agency (EPA) estimates that, per year, 7,000 to 30,000 of these lung cancer deaths are related to exposure to radon gas. One estimate is that exposure to both tobacco and radon is approximately 10 times as hazardous as exposure to either one of these pollutants by itself. However, there have been few direct studies linking radon gas exposure in houses to increased incidence of lung cancer. Estimates of such linkage come from studies of people who have experienced high exposure to radiation through such activities as mining uranium.

In terms of the implied risk, large concentrations of radon are indeed hazardous, and it has not been shown that small concentrations are harmless. The EPA has set 4.0 picoCuries of radon gas per liter of air (4.0 pCi/L) as the radioactivity level beyond which radon gas is considered hazardous. The radioactivity level of 4.0 pCi/L is only an estimate of a concentration target to which indoor levels should be reduced. The average outdoor concentration of radon gas is approximately 0.4 pCi/L, and the average indoor level is about 1.0 pCi/L. The comparable risk at 4.0 pCi/L, for a nonsmoker, is about the same as the risk of drowning. For a smoker, the comparable risk at this level is about 100 times the risk of dying in an airplane crash (**Figure 19.A**). The risk of radon exposure can also be estimated according to the number of people who might contract lung cancer, as shown in Figure 19.A. These estimations have been difficult to verify. One U.S. study of nonsmoking women reported that a significant positive relationship between radon exposure and lung cancer was not found.[19] Another study in Sweden reported a statistically significant positive relationship between exposure to radon gas in homes and lung cancer.[20] The latter concluded that residential exposure to radon gas is an important contributing factor in the incidence of lung cancer in the general population of Sweden.

The Geology of Radon Gas

Both rock type and geologic structure are important in determining how much radon is likely to reach the surface of Earth. Uranium-238 concentrations in rocks and soil can vary greatly. Some rock types, such as sandstone, generally contain less than 1 ppm U-238. The actual amount of radon that reaches the surface of Earth is related to the concentration of uranium in the rock and soil, as well as to the efficiency of the transfer processes from the rock or soil to soil–water and soil–gas.

Some regions of the United States contain bedrock with an above-average natural concentration of uranium. The Reading Prong that covers parts of Pennsylvania, New Jersey, and New York is known for elevated concentrations of radon gas (**Figure 19.B**). The Reading Prong is a region of linear, rounded hills and ridges with relief of 100 to 200 m. The hills and ridges are underlain by hard igneous and metamorphic rock of Precambrian age with steep slopes eroded by short, steep streams.

Two areas in Florida have elevated concentrations of uranium, in addition to radioactive potassium from phosphate-rich rocks. Many other states, including Illinois, New Mexico, South Dakota, North Dakota, and Washington, also have identified areas with elevated indoor radon concentrations. One type of dark shale found in the Santa Barbara, California, area has been identified as a significant radon gas producer.

Geologic structures such as shear zones, fracture zones, and faults are commonly enriched with uranium and can produce elevated concentrations of radon gas in the overlying soils.[21,22] One study in southern Virginia found that shear zones in granite rock are associated with as much as a tenfold increase in the concentration of radon in overlying soils. Furthermore, one of the highest indoor levels of radon in the United States is identified over shear zones in Boyertown, Pennsylvania.[22] In Santa Barbara, California, one of the

RADON RISK IF YOU SMOKE

Radon level	If 1,000 people who smoked were exposed to this level over a lifetime...	The risk of cancer from radon exposure compares to...	WHAT TO DO: Stop smoking and...
20 pCi/l	About 135 people could get lung cancer	← 100 times the risk of drowning	Fix your home
10 pCi/l	About 71 people could get lung cancer	← 100 times the risk of dying in a home fire	Fix your home
8 pCi/l	About 57 people could get lung cancer		Fix your home
4 pCi/l	About 29 people could get lung cancer	← 100 times the risk of dying in an airplane crash	Fix your home
2 pCi/l	About 15 people could get lung cancer	← 2 times the risk of dying in a car crash	Consider fixing between 2 and 4 pCi/l
1.3 pCi/l	About 9 people could get lung cancer	(Average indoor radon level)	(Reducing radon levels below 2 pCi/l is difficult)
0.4 pCi/l	About 3 people could get lung cancer	(Average outdoor radon level)	

Note: If you are a former smoker, your risk may be lower.

RADON RISK IF YOU'VE NEVER SMOKED

Radon level	If 1,000 people who never smoked were exposed to this level over a lifetime...	The risk of cancer from radon exposure compares to...	WHAT TO DO:
20 pCi/l	About 8 people could get lung cancer	← The risk of being killed in a violent crime	Fix your home
10 pCi/l	About 4 people could get lung cancer		Fix your home
8 pCi/l	About 3 people could get lung cancer	← 10 times the risk of dying in an airplane crash	Fix your home
4 pCi/l	About 2 people could get lung cancer	← The risk of drowning	Fix your home
2 pCi/l	About 1 person could get lung cancer	← The risk of dying in a home fire	Consider fixing between 2 and 4 pCi/l
1.3 pCi/l	Less than 1 person could get lung cancer	(Average indoor radon level)	(Reducing radon levels below 2 pCi/l is difficult)
0.4 pCi/l	Less than 1 person could get lung cancer	(Average outdoor radon level)	

Note: If you are a former smoker, your risk may be higher.

FIGURE 19.A Estimated risk associated with radon These estimates are calculated as long-term exposure risks for a person living about 70 years and spending about 75 percent of the time in the home with a designated level of radon. *(From U.S. Environmental Protection Agency. 1986. A Citizen's Guide to Radon. OPA-86-004)*

highest concentrations of in-house radon measured to date occurs at the crest of an active fold (i.e., anticline) involving superficial sand beds that overlie organic-rich shale at shallow depth. It is hypothesized that open tension fractures at the crest of the fold allow the radon gas to diffuse upward to the surface.

The amount of radon gas that escapes from bedrock and soil particles is greatly influenced by water content. Relatively high moisture content favors the trapping of radon gas in the spaces between soil and fractures in rocks. This results because the presence of water greatly reduces the distance that radon can travel as a result of radioactive decay from its parent material, such as radium-226. Movement of radon gas from fractures in rock and pore spaces in soil is facilitated by relatively low moisture content. That is, the process of diffusion of radon gas is much greater in unsaturated material. Thus, the moisture content affects the amount of radon that may reach the surface of Earth in two opposing ways:

1. High moisture content increases the chances of radon entering and residing in the pore spaces in rock fractures or between soil grains.
2. High moisture content tends to inhibit radon from moving through the pore spaces in rocks and soils.

As a result of these two factors, there is an optimal water content that will result in the maximum amount of radon

FIGURE 19.B The Reading Prong area is located in the eastern United States, where high levels of indoor radon were first discovered in the early 1980s. *(Modified after U.S. Geological Survey. 1986. U.S.G.S. Yearbook)*

that actually reaches the surface of Earth. In some soils, this optimal water content is approximately 20 to 30 percent.[1]

How Radon Gas Enters Homes

Radon gas enters homes by three major pathways (Figure 19.C):[23]

- As a gas, migrating up from soil and rocks into basements and other parts of houses
- In groundwater pumped into wells
- In construction materials, such as building blocks, made of substances that emit radon gas

Most of the early interest in radon gas in homes was initiated because of the use of building materials potentially containing high concentrations of radium, a product of the radioactive decay of uranium (see Chapter 16).

There is concern that granite countertops, so popular in kitchens today, are contaminating homes with dangerous levels of radon gas. Granite does have uranium in some of the minerals that make up the rock. Granite rock, with fracture zones that allow radon gas to migrate upward,

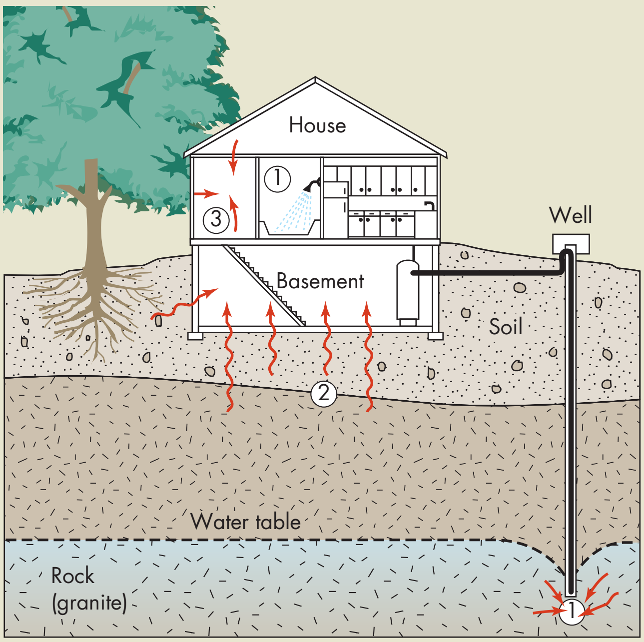


FIGURE 19.C How radon may enter homes (1) Radon in groundwater enters the well and goes to the house, where it is used as drinking water and for dishwashing, showers, and other purposes. (2) Radon gas in rock and soil migrates into the basement through cracks in the foundation and pores in construction. (3) Radon gas is emitted from construction materials used in building the house. *(From Environmental Protection Agency)*

has been recognized in southern Virginia as a localized radon hazard. The important observation is that, in order to move up from soil and rock into our homes, radon gas needs pathways, such as fractures in the rock or open spaces between soil particles. Granite that is used in countertops is not very porous. If the rock has open fractures, it will break easily and can't be used for countertops. Therefore, even though granite has some uranium in the rock, it will generally yield very little radon gas. Radon entering homes from the soil beneath homes over weathered uranium-bearing rocks (i.e., granite or sedimentary rocks, such as some shale) is a significant public health risk. However, according to the EPA, the risk from granite countertops or other building materials is not thought to be a serious problem.

Radon is commonly found in homes because it is a gas that can move through the small openings in soils and rocks. Radon migrates up with soil gases and seeps through concrete floors and foundations, floor drains, or small cracks and pores in block walls. Radon enters homes for the same reason that smoke goes up a chimney, in a process known as the *chimney*, or *stack*, *effect*: Houses are generally warmer than the surrounding soil and rock, so, as the gases and air rise, radon is drawn into the house. Wind is an additional factor in radon contamination because it increases air flow into and out of buildings. Radon also enters homes through the water supply, particularly if the home is supplied by a private well; however, this contribution is usually much smaller than the contribution of gas seeping up through house foundations. Radon is released into the air when the water is used for daily functions such as showering, dishwashing, and clothes washing. In general, approximately 10,000 pCi/L of radon in water will produce about 1 pCi/L of radon in indoor air.

Scope and Perception of the Problem

Since 1985, awareness of radon gas has increased in the United States. Nevertheless, people have a difficult time focusing on a problem that they cannot see, smell, hear, or touch. There is no good estimate of the number of homes in the United States that may have elevated concentrations of radon gas. The tests that have been done indicate that approximately 1 in 12 homes surveyed have an indoor radon level above 4 pCi/L. If this rate is a good average, then approximately 7 million homes in the United States would have elevated rates, and millions more will need to be tested.

Reducing Concentrations of Radon Gas in Homes

A successful program to reduce or limit a potential hazard from radon gas in homes focuses on three major strategies:[24,25]

- Improving home ventilation by keeping more windows open or using fans
- Locating and sealing points of radon gas entry
- Using construction methods that provide a venting system

The simplest method of reducing the radon concentration is to increase the ventilation in the home. Sometimes this is sufficient to solve the problem. Sealing cracks in the foundation can also reduce radon entry, particularly if it is done in specific sites where the radon is actually entering the house. Detectors are available to help identify such locations. Unfortunately, this method often fails to solve the problem, and new cracks may form. A variety of construction options are open to the homeowner, including installing venting systems in a basement or crawl space. If the house is built on a slab, then subslab ventilation systems may be installed.

There is good and bad news concerning radon gas. The bad news is that many parts of the United States and other parts of the world have relatively high emissions of radon gas from soil and rocks, and the radiation is producing a hazard in homes. The good news is that, in most cases, the problem can be fixed relatively easily. Even if a ventilation system is required, it costs only a few thousand dollars, generally a small percentage of the value of the home.

Future research may show that health risks from radon gas exposure are not as great as predicted by the EPA. Some scientists are skeptical and think that the hazard level of 4 pCi/L may be set too low.[26] Nonetheless, it is important for people to become informed about this potential problem. Taking appropriate action to deal with the possibility of radon gas in homes is difficult; people seem to be more concerned with property values than with health issues. Both recognizing the whole picture and knowing that reducing radon gas is a solvable problem can reduce our fears about radon.

150 million people in the United States are exposed to air pollution that may cause lung disease, contributing to more than 300,000 deaths per year. Some estimates of the health cost associated with air pollution in the United States place it at about $50 billion per year.

Effects on Human Artifacts. The effects of air pollution on buildings and monuments include discoloration, erosion, and decomposition of construction materials, as discussed in the section on acid rain in Chapter 16.

Aesthetic Effects. Air pollutants affect visual resources by discoloring the atmosphere and reducing visual range and atmospheric clarity. We cannot see as far in polluted air as in clean air, and what we do see has less color contrast. Once limited to cities, these effects now extend even to the wide-open spaces of the United States. For example, near the junction of New Mexico, Arizona, Colorado, and Utah, emissions from the Four Corners fossil fuel–burning power plant are altering air clarity in an area where, on a clear day, visibility was once 80 km (50 mi) from a mountaintop.[28,29]

Sources of Air Pollution

The two primary types of air pollution sources are stationary and mobile. *Stationary sources* include those with a relatively fixed location, such as *point sources, fugitive sources,* and *area sources. Point sources* emit air pollutants from one or more discrete controllable sites, such as the smokestacks of industrial power plants. *Fugitive sources* generate air pollutants from open areas exposed to wind processes. Examples include dirt roads, construction sites, farmlands, storage piles, and surface mines. *Area sources* are locations that emit air pollutants from several sources within a well-defined area, as, for example, small urban communities or areas of intense industrialization within an urban complex. *Mobile sources* move from place to place while yielding emissions. Mobile sources of pollution include automobiles, aircraft, ships, and trains.[29]

Air Pollutants

The major air pollutants occur either in gaseous form or as particulate matter (PM). The *gaseous pollutants* include sulfur dioxide (SO_2), nitrogen oxides (NO_x, where x represents a variable number of oxygen atoms, usually 1, 2, or 3), carbon monoxide (CO), ozone (O_3), volatile organic compounds (referred to as VOCs), hydrogen sulfide (H_2S), and hydrogen fluoride (HF). Particulate-matter pollutants are particles of organic or inorganic solid or liquid substances. Those that are less than 10 μm (i.e., 10 millionths of a meter) in diameter are designated PM 10. Those that are less than 2.5 μm in diameter are designated PM 2.5. We will discuss particulates in some detail, as they often have significant geologic components.

Air Toxins

Air pollutants known to cause cancer or other serious health problems are classified as **air toxins**. This category of air pollutants is classified by (1) whether they cause cancer and (2) their tendency to cause respiratory, reproductive, neurological, or immune diseases. Toxicity is based on exposure to an air toxin by breathing the pollutant. The extent to which a specific toxin affects the health of an individual depends on the toxicity of the pollutant, the frequency and duration of exposure, the concentration of the pollutant a person is exposed to, and the general health of the person. More than 150 chemicals, including ammonia, chlorine gases, and hydrogen sulfide, are evaluated for toxicity. The four states with the most serious exposure to air toxins are California, New York, Oregon, and New Jersey. The three cleanest states are Montana, Wyoming, and South Dakota. Evaluation of air toxins as a category of air pollutants is a relative new activity but will add increased understanding of toxic air pollution problems and, hopefully, lead to improved air quality.[30]

Primary and Secondary Pollutants

Air pollutants may be classified as primary and secondary, according to their origin. **Primary pollutants** are emitted directly into the air and include particulate matter, sulfur oxides, carbon monoxide, nitrogen oxides, and hydrocarbons. **Secondary pollutants** are produced when primary pollutants react with normal atmospheric compounds. For example, ozone forms over urban areas through reactions among primary pollutants, sunlight, and natural atmospheric gases. Thus, ozone becomes a serious secondary pollution problem on bright, sunny days in areas with abundant primary pollution. Although particularly well documented for southern California cities such as Los Angeles, ozone becomes a secondary pollutant worldwide under appropriate conditions.

TABLE 19.1 Major Natural and Human-Produced Components of Air Pollutants

Air Pollutant	Emissions (% of total): Natural	Emissions (% of total): Human-Produced	Major Source of Human-Produced Component	%
Sulfur oxides (SO_x)	50	50	Combustion of fuels (stationary sources, mostly coal)	84
			Industrial processes	9
Nitrogen dioxide (NO_2): light yellow-brown to reddish gas		Nearly all	Automobiles	37
			Combustion of fuels (stationary sources, mostly natural gas and coal)	38
Carbon monoxide (CO)	91	9	Automobiles	54
Ozone (O_3)	A secondary pollutant derived from reactions with sunlight, NO_2, and oxygen (O_2)		Concentration that is present depends on reaction in lower atmosphere involving hydrocarbons and, thus, automobile exhaust	
Hydrocarbons (HC) (volatile organic compounds)	84	16	Automobiles	27
			Industrial processes	7
Particulates	85	15	Dust	85
			Industrial processes	7
			Combustion of fuels (stationary sources)	8

The primary pollutants that account for nearly all air pollution problems are carbon monoxide, nitrogen oxides, sulfur oxides, volatile organic compounds, and particulates. Each year, about 50 million metric tons of these materials enter the atmosphere of the United States as a result of human-related processes. At first glance, this amount of pollutants appears to be very large. However, if uniformly distributed in the atmosphere, this would amount to only a few parts per million by weight. Unfortunately, pollutants are not uniformly distributed but tend to be released, produced, and concentrated locally or regionally. For example, large cities' weather and climatic conditions combine with urbanization and industrialization to produce local air pollution problems.

Major air pollutants, in terms of their natural and human-induced components, and their effects on people, plants, and materials, are shown in **Table 19.1** and **Table 19.2**.

Particulate Matter: PM 10 and PM 2.5

Particulate-matter pollutants are small particles of solid or liquid substances that are designated PM 10 or PM 2.5, depending on size. PM 10 particles are less than 10 μm in diameter; they are released into the atmosphere by many natural processes and human activities. About 85 percent of emissions of particulates are from natural sources (Table 19.1). Dust from eroding land, volcanic eruptions, fires, and modern farming all add large amounts of particulate matter to the air. Burning of crop residue (from wheat fields in North Dakota, bluegrass in Idaho, rice in California, and sugarcane in Hawaii) emits large amounts of PM 2.5 from smoke and soot into the atmosphere. Nearly all industrial processes release particulates into the atmosphere, as does the burning of fossil fuels. Much particulate matter is easily visible as smoke, soot, or dust, but some

TABLE 19.2 Effects of Selected Air Pollutants on People, Plants, and Materials

Pollutant	Effects on People[1,2]	Effects on Plants[1,3]	Effects on Materials[1,4]
Sulfur dioxide (SO_2): a colorless, odorless gas near the surface of Earth	Increase in chronic respiratory disease; shortness of breath; narrowing of airways for people with asthma	Bleaching of leaves; decay and death of tissue; younger leaves are more sensitive than older; sensitive crops and trees include alfalfa, barley, cotton, spinach, beets, white pine, white birch, and trembling aspen; if oxidized to sulfuric acid, causes damage associated with acid rain	If oxidized to sulfuric acid, damages buildings and monuments; corrodes metal; causes paper to become brittle; turns leather to red-brown dust; SO_2 fades dyes of fabrics, damages paint
Nitrogen oxides (NO_x)	Except for odor, is a mostly nonirritating gas; may aggravate respiratory infections and symptoms (sore throat, cough, nasal congestion, fever) and increase risk of chest cold, bronchitis, and pneumonia in children	No perceptible effects on many plants, but may suppress plant growth and may be beneficial at low concentrations; if oxidized to nitric acid, causes damage associated with acid rain	Causes fading of textile dyes; if oxidized to nitric acid, may damage buildings and monuments
Carbon monoxide (CO): a colorless, odorless gas; extremely toxic	Reduces the ability of the circulatory system to transport oxygen; headache, fatigue, nausea; impairs performance of tasks that require concentration; reduces endurance; may be lethal, causing asphyxiation	None perceptible	None perceptible
Ozone (O_3) (in lower atmosphere): colorless, unstable gas, slight sweet odor; produced by chemical reactions between sunlight with hydrocarbons from automobile exhaust	Strong irritant; aggravates asthma; injury to cells in respiratory system; decreased elasticity of lung tissue; coughing; chest discomfort; eye irritation	Flecking, stippling, spotting, and/or bleaching of plant tissue (leaves, stems, etc.); oldest leaves are most sensitive; tips of needles of conifers become brown and die; reduction of yields and damage to crops, including lettuce, grapes, and corn	Cracks rubber; reduces durability and appearance of paint; causes fabric dyes to fade
Particulate matter, PM 2.5 and PM 10: small particles, or solid or liquid materials, less than 2.5 μm or 10 μm, respectively	Increased chronic and acute respiratory diseases; depending on chemical composition of particulates, may irritate tissue of throat, nose, lungs, and eyes[5]	Depending on chemical composition of particles, may damage trees and crops; dry deposition of SO_2, when oxidized, is a form of acid rain	Contributes to and may accelerate corrosion of metal; may contaminate electrical contacts; damages paint appearance and durability; fades textile dyes

[1] Effects are dependent upon dose (i.e., concentration of pollutant and time of exposure) and susceptibility of people, plants, and materials to a particular pollutant. For example, older people, children, and those with chronic lung diseases are more susceptible to pollutants such as O_3, SO_2, and NO_x.

[2] Annual U.S. losses exceed $50 billion.

[3] Annual U.S. losses to crops are $1 billion to $5 billion.

[4] Annual U.S. losses exceed $5 billion.

[5] Visible as dust and smoke.

Modified from U.S. Environmental Protection Agency; Bunbel, R. W., Fox, D. L., Turner, D. B., and Stern, A. C. 1994. *Fundamentals of Air Pollution,* 3rd ed. San Diego: Academic Press; and Godish, T. 1997. *Air Quality,* 3rd ed. Boca Raton, FL: Lewis Publishers.

particulate matter is not readily apparent. Particulates include airborne asbestos particles and small particles of heavy metals, such as arsenic, copper, lead, and zinc, which are usually emitted from industrial facilities, such as smelters.

Very fine particle pollutants with particles less than 2.5 μm in diameter (PM 2.5) cause the greatest damage to the lungs. Sulfates and nitrates are two of the most significant fine-particle pollutants. Both of these compounds are mostly secondary pollutants and are produced in the atmosphere through chemical reactions between sulfur dioxide or nitrogen oxides and normal atmospheric constituents. Sulfates, in the form of sulfuric acid and nitric acid, are formed by these reactions and are then precipitated as acid rain.[29] When measured, particulate matter is often referred to as *total suspended particulates* (*TSP*).

Particulates affect human health, ecosystems, and the biosphere (Table 19.2). Particulates entering the lungs may lodge there, producing chronic effects on respiration; asbestos is particularly dangerous in this regard. Dust raised by road building and plowing is deposited on the surfaces of green plants, possibly interfering with both the plants' absorption of carbon dioxide and oxygen and their release of water; heavy dust may affect the breathing of animals. Particulates in the United States are believed to contribute to the deaths of 60,000 people per year. In cities, it is estimated that up to 9 percent of all deaths are associated with particles, and the risk of mortality is 15 percent to 25 percent higher in cities with the highest levels of fine-particulate pollution.[31]

Particulates associated with large construction projects may kill organisms and damage large areas, changing species composition, altering food chains, and generally affecting ecosystems. In addition, modern industrial processes have greatly increased the total suspended particulates in the atmosphere. Particulates block sunlight and, thus, cause changes in climate, which can have lasting effects on the biosphere.[32]

Asbestos. *Asbestos* particles have only recently been recognized as a significant hazard to humans. In the past, asbestos was treated rather casually, and people working in asbestos plants were not protected from dust. Asbestos was used in building insulation and in brake pads for automobiles. As a result, asbestos fibers are found throughout industrialized countries, especially in European and North American urban environments. In one case, asbestos products were sold in burlap bags that were eventually reused in plant nurseries and other secondary businesses, thereby further spreading the pollutant. Some asbestos particles are believed to cause cancer, so asbestos must be carefully controlled (see Chapter 3).

Lead. *Lead* is an important constituent of automobile batteries and other industrial products. When used as a gasoline additive, lead improves the performance of automobile engines. Previously, in the United States, lead emitted into the environment via automobile exhaust was widely deposited, reaching high levels in soils and waters along roadways (see A Closer Look: Lead in the Environment). Once released, lead can be transported through the air as particulates to be taken up by plants through the soil or deposited directly on plant leaves. Thus, it enters terrestrial food chains and may be ingested by people. When lead is carried by streams and rivers, deposited in quiet waters, or transported to the ocean or lakes, it is taken up by aquatic organisms and, thus, enters aquatic food chains. Although lead is no longer used in gasoline in the United States, it is still used in other parts of the world.

Cadmium. Some of the *cadmium* in the environment comes from coal ash, which is widely dispersed from smokestacks and chimneys. Cadmium exists as a trace element in the coal, at a very low concentration of 0.05 parts per million. When the coal ash falls on plants, the cadmium is incorporated into plant tissue and concentrated. As cadmium moves up through the food chain, it undergoes *biomagnification* at each higher level. Herbivores have approximately three times the concentration of green plants, and carnivores have approximately three times the concentration of herbivores.

Urban Air Pollution

Air pollution is not distributed uniformly around the world. Much of it is concentrated in and around urban areas, where automobiles and heavy industry emit enormous amounts of waste into the environment. The visible air pollution known as smog is

present in nearly all urbanized areas, although it is much worse in some regions than in others. In this section, we will consider the factors contributing to urban air pollution and discuss the composition and formation of smog.

Influence of Meteorology and Topography

The extent to which air pollution occurs in an urban area depends largely on emission rates, topography, and weather conditions; these factors determine the rate at which pollutants are concentrated and transported away from their sources or converted to harmless compounds in the air. When the rate of pollutant production exceeds the rates of transport and chemical transformation, dangerous conditions can develop.

Meteorological conditions can determine whether air pollution is only a nuisance or a major health problem. Most pollution periods in the Los Angeles Basin and other smoggy areas do not cause large numbers of deaths. However, serious pollution events can develop over a period of days and lead to an increase in deaths and illnesses.

Restricted circulation in the lower atmosphere due to the formation of an *inversion layer* may lead to a pollution event. An **atmospheric inversion** occurs when warm air overlies cool air. An inversion layer is particularly a problem when there is a stagnated air mass. **Figure 19.3** shows two types of developing inversions that may worsen air pollution problems. Figure 19.3a shows descending warm air from inland warm arid areas forming a semipermanent inversion layer. Because the mountains act as a barrier to the pollution, polluted air moving in response to the sea breeze and other processes tends to move up canyons, where it is trapped. The air pollution that develops occurs primarily during the summer and fall, when warm inland air comes over the mountains and overlies cooler coastal air, forming the inversion. This example is representative of the situation in the Los Angeles area.

Figure 19.3b shows a valley with relatively cool air overlain by warm air, a situation that can occur in several ways. When cloud cover associated with a stagnant air mass develops over an urban area, the incoming solar radiation is blocked by the clouds, which absorb some of the energy and, thus, heat up. On or near the ground, the air cools. If the humidity

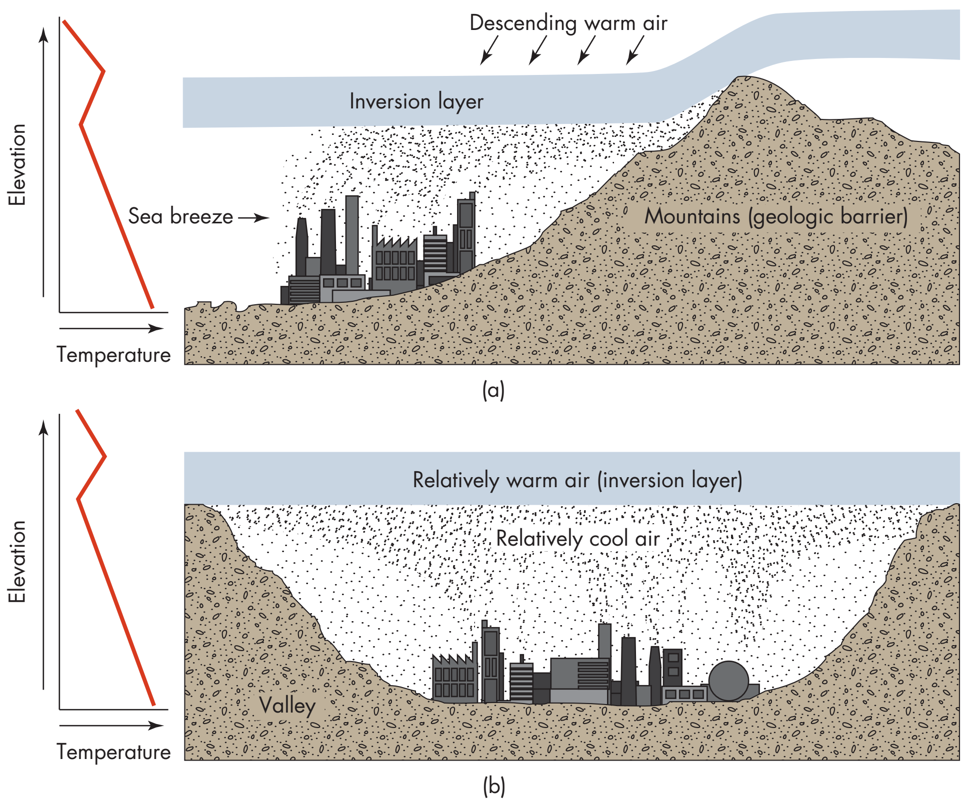


FIGURE 19.3 Temperature inversion Two causes for the development of a temperature inversion, which may aggravate air pollution problems: (a) Descending warm air from inland arid areas forms a semipermanent inversion layer. (b) A valley with relatively cool air is overlain by warm air.

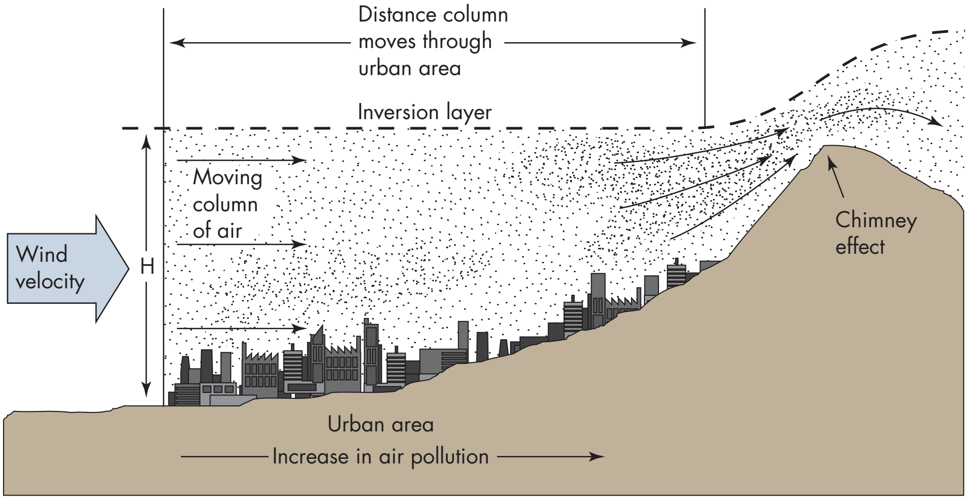


FIGURE 19.4 How air pollutants may be concentrated As wind velocity increases and the mixing layer (shown here as H) becomes thicker, there is less potential for air pollution. As both the emission rate and the downwind length of the city increase, there is a greater potential for air pollution. The "chimney effect" allows polluted air to move over a mountain down into an adjacent valley.

is high, a thick fog may form as the air cools. Because the air is cool, people living in the city burn more fuel to heat their homes and factories, thus delivering more pollutants into the atmosphere. As long as the stagnant conditions exist, the pollutants continue to accumulate.

Potential for Urban Air Pollution

The potential for air pollution in urban areas, as illustrated in Figure 19.4, is determined by the following factors:

- Rate of pollutant emissions
- Distance that a mass of air moves through urban air pollution sources
- Average speed of the wind
- Height of the mixing layer—that is, the height to which potential pollutants may be thoroughly mixed in the lower atmosphere

If we assume that there is a constant rate of emission of air pollutants, the mass of air will collect more and more pollutants as it moves through the urban area. Thus, the concentration of pollutants in the air is directly proportional to the first two factors: As either the emission rate or the downwind travel distance increases, so does the concentration of pollutants. Conversely, city air pollution decreases with increased wind velocity and the height of mixing. The stronger the wind and the higher the mixing layer, the lower the pollution.

If an inversion layer is present near a geologic barrier such as a mountain, a "chimney effect" may let the pollutants spill over the top of the barrier (see Figure 19.4). This effect has been noticed in the Los Angeles Basin, where pollutants can climb several thousand meters, damaging mountain pine trees and other vegetation.

Smog Production

Wherever many sources are producing air pollutants over a wide area—as, for example, automobiles in Los Angeles—there is the potential for the development of smog. The two major types of smog are *sulfurous smog*, sometimes referred to as London-type smog or gray air, and *photochemical smog*, sometimes called L.A.-type smog or brown air. **Sulfurous smog** is primarily produced by burning coal or oil at large power plants. Under certain meteorological conditions, the sulfur oxides and particulates produced by this burning combine to produce concentrated sulfurous smog.

Reactions that produce **photochemical smog** are complex, involving nitrogen oxides (NO_x), hydrocarbons, and solar radiation. Development of photochemical smog is related to automobile use. In southern California, for example, when commuter traffic begins to build up early in the morning, the concentrations of nitrogen oxide (NO) and hydrocarbons begin to increase. At the same time, the amount of nitrogen dioxide (NO_2) may decrease, due to the sunlight-driven reaction of NO_2 that produces NO plus atomic oxygen (O). The atomic oxygen is then free to combine with molecular oxygen to form ozone (O_3), increasing ozone levels after sunrise. By midmorning, oxidized hydrocarbons react with NO to increase the concentration of NO_2. This reaction causes the NO concentration to decrease and allows

ozone to build up, producing a midday peak in ozone and a minimum in NO. As the smog matures, visibility is reduced by light-scattering from small particles.

Future of Air Pollution in Urban Areas

Air pollution levels in many cities in the United States and other developed countries have a mixed but, generally, improving record. Data from major U.S. metropolitan areas in recent years show a decline in the total number of days characterized as unhealthful and very unhealthful, suggesting that the nation's air quality is improving (**Figure 19.5a**). This suggested improvement has occurred despite the fact that there are many more motor vehicles, population has increased, and energy consumption has increased (Figure 19.5b). However, most major urban areas, such as New York and Los Angeles, still have unhealthy air much of the time. Furthermore,

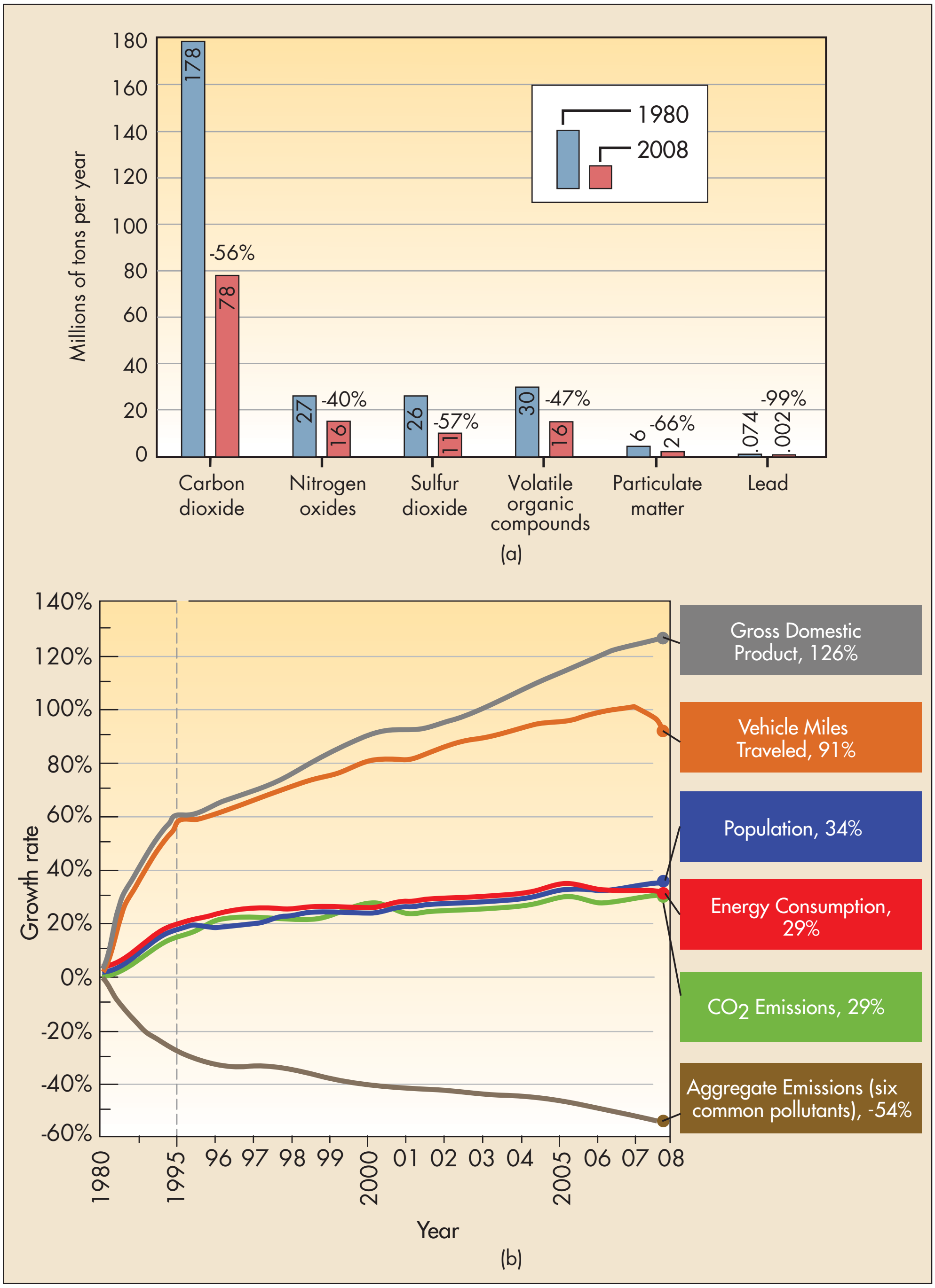


FIGURE 19.5 Air pollution trends (a) Selected trends in the United States since 1980. (b) Emissions have decreased as population has increased, as we have driven automobiles more, and as we have used more energy. *(Environmental Protection Agency. 2008.* Air Quality Trends Through 2007. *www.epa.gov)*

many U.S. cities have poor air quality at least 30 days per year. According to this criterion, millions of Americans still live in cities that have hazardous air pollution for a significant portion of each year.[27]

The encouraging news is that emissions of some major air pollutants in the United States are decreasing. For example (Figure 19.5a):[33]

- SO_2 emissions since 1970 have declined 57 percent as a result of burning less coal, using low-sulfur coal, and treating effluent gases from power plants before release into the environment.
- Emissions of volatile organic compounds (including hydrocarbons) have decreased since 1970 to levels not recorded since the 1940s. A decrease of about 47 percent has resulted in part from the successful control of automobile emissions and substitutions of water-based components instead of VOC components in products such as asphalt.
- Lead emissions have decreased by 99 percent since 1980, mostly as a result of removing lead from gasoline.
- Emissions of nitrogen oxides have been reduced by 40 percent since 1980, mostly as a result of emission controls in automobiles and power plants.
- Concentrations of ozone (a secondary pollutant in the lower atmosphere) since 1990 have been reduced about 9 percent as a result of reducing emissions of nitrogen oxides from automobiles.
- Human-caused emissions of particulates (most of which are natural) have been reduced by about 60 percent as a result of improved emission control measures from a variety of sources.

Indoor Air Pollution

Indoor air pollution is one of the most serious environmental health hazards that people face in their homes and workplaces.[34,35] In recent years, buildings have been constructed more tightly, often with windows that cannot be opened, to save energy. As a result, in many buildings, air is filtered. Unless filters are maintained properly, indoor air can become polluted with a variety of substances, including smoke, chemicals, disease-carrying organisms, and radon, a naturally occurring radioactive gas suspected of causing lung and other cancers (see A Closer Look: Radon Gas). It was shown that the virus responsible for the respiratory infection known as Legionnaires' disease is transported through air filters and ventilation systems of buildings.

A variety of materials found in our buildings may release minute amounts of chemicals and other materials into the nearby air. In some buildings, asbestos fibers are slowly released from insulation and other fixtures; people exposed to a particular type of asbestos fiber may develop a rare form of lung cancer. The poisonous gases carbon monoxide and nitrogen dioxide may be released in homes from unvented or poorly vented gas stoves, furnaces, or water heaters. Formaldehyde, present in some insulation materials and wood products used in home construction, is known to irritate the ears, nose, and throat. Radon is present in some building materials, such as concrete blocks and bricks manufactured from materials with a high radon concentration. Buildings that lack systems that recirculate clean air are likely to have indoor pollution problems. Improvements in indoor air quality have been developed; most of these stress improved clean air circulation and reduced pollutant emissions.

Interestingly, indoor air pollution existed centuries ago. In 1972, the body of a fourth-century Eskimo woman was discovered on St. Lawrence Island in the Bering Sea. The woman evidently was killed during an earthquake or a landslide, and her body was frozen soon after death. Detailed autopsies showed that the woman suffered from black lung disease, which afflicts some coal miners today. Anthropologists and medical personnel concluded that the woman breathed highly polluted air for a number of years. They speculated that the air pollution was, in part, due to hazardous fumes given off from lamps that burned seal and whale blubber.[36]

19.4 Waste Management and Geology

People in the United States and throughout the rest of the world are facing a tremendous solid-waste disposal problem, particularly in growing urban areas. The problem boils down to the simple fact that urban areas are producing too much waste, and there is too little acceptable space (often from a

social perspective more than a physical shortage of space) for disposal. About half the cities in the United States are estimated to be running out of landfill space. Cost is another limiting factor: Expenditures for landfill disposal have skyrocketed in recent years.[37]

All types of societies produce waste, but industrialization and urbanization have caused an ever-increasing effluence that has greatly compounded the problem of waste management. Although tremendous quantities of liquid and solid waste from municipal, industrial, and agricultural sources are being collected and recycled, treated, or disposed of, new and innovative programs are necessary if we are to keep ahead of what might be called a waste crisis. Disposal or treatment of liquid and solid waste by federal, state, and municipal agencies costs billions of dollars every year. In fact, it is one of the most costly environmental expenditures of governments, accounting for the majority of total environmental expenditures.

A possible solution to the solid waste problem would be to develop new disposal facilities. Unfortunately, no one wants to live near a waste disposal site, be it a sanitary landfill for municipal waste, an incinerator facility that can reduce the volume of waste by 75 percent, or a disposal operation for hazardous chemical materials. This obviously creates serious siting problems, even if the local geographic, geologic, and hydrologic environment is favorable. The siting problem also involves issues of *social justice*. Waste-management facilities are all too frequently located in areas where the residents are of low social and economic status or belong to a minority ethnic group or race.

Integrated Waste Management

There is a growing awareness that many of our waste-management programs simply involve moving waste from one site to another and not properly disposing of it. For example, waste from urban areas may be placed in landfills, but, eventually, these may cause further problems because of the production of methane gas (which is a resource, if managed properly) or noxious liquids that leak from the site to contaminate the surrounding areas. Disposal sites are also capable of producing significant air pollution. It is safe to assume that waste management is going to be a public concern for a long time. Of particular importance will be the development of new methods of waste management that will not endanger the public health or cause a nuisance.

Integrated waste management (IWM) emerged in the 1980s as a set of management alternatives, including reducing resources, reusing, recycling, composting, landfilling, and incinerating.[37] **Reduce, reuse, and recycle** are the three *R*s of IWM. Recycling can reduce the weight of urban refuse disposed in landfills by approximately 50 percent.

The recycling component of IWM, which has been seriously pursued for several decades, has generated entire systems of waste management that have produced tens of thousands of jobs while reducing the amount of urban waste from homes in the United States sent to landfills from 90 percent in the 1980s to about 65 percent today. In fact, many firms have combined waste reduction with recycling to reduce the waste they deliver to landfills by over 50 percent. Despite this success, IWM is criticized for not effectively advancing policies to prevent waste production by overemphasizing recycling. In the long term, waste management policies that rely on recycling cannot be successful. If we continue with today's management of waste, in approximately 50 to 70 years, when the U.S. population has doubled again, we will be producing the same volume of waste sent to landfills that we do today, given a 50 percent rate of recycling. Clearly, emphasizing recycling is not a sustainable solution to our waste problem. With this in mind, the concept of IWM needs to be rethought and expanded to include what is termed *materials management*.[38]

Materials Management

Materials management is part of IWM, but it provides a new goal. That goal is *zero production of waste*, so that what is now thought of as waste will be a resource! This is a visionary goal, requiring a more sustainable use of materials, combined with resource conservation. It is believed that materials management as an extension of IWM can be established by:[38]

- Eliminating subsidies for extraction of virgin materials, such as timber, minerals, and oil.
- Establishing "green building" incentives that use recycled materials and products in new construction.

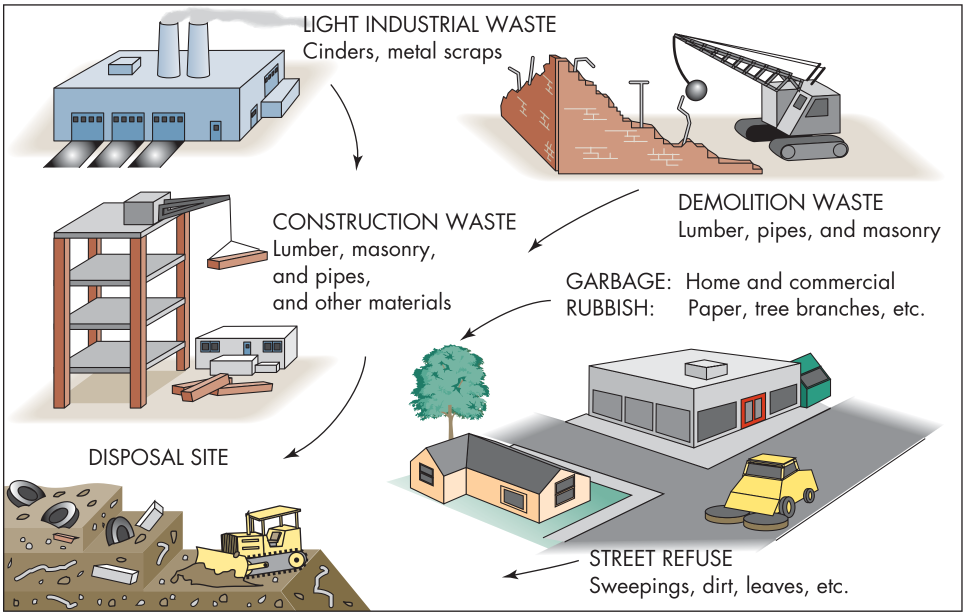


FIGURE 19.6 Types of refuse materials A variety of materials are commonly transported to disposal sites.

- Establishing financial penalties for production of products that do not meet the objectives of material management practices.
- Providing financial incentives for industrial practices and products that benefit the environment by enhancing sustainability, such as encouraging products that reduce waste production and use recycled materials.
- Providing incentives for the production of new jobs in the technology of materials management, as well as incentives for practicing reducing, recycling, and reusing resources. This is the essence of materials management and sustainable resource utilization.

The concept of materials management for "zero waste" is part of what is known as **industrial ecology**. The idea is to produce urban and industrial systems that model natural ecosystems, where waste from one part of the system is a resource for another part.

With this introduction to modern trends and integrated waste management, it is advantageous to break the management treatment and disposal of waste into two main categories: solid waste disposal and hazardous waste management.

TABLE 19.3 Generalized Composition of Urban Solid Waste (by Weight) Before Recycling for 1986 and 2008

Material	1986 (%)	2008 (%)
Paper	36	31
Yard waste	20	13
Plastics	7	12
Metals	9	8
Food waste	9	13
Glass	8	5
Wood	4	7
Other (includes rubber, leather and textiles)	7	11

Ujihara, A. M., and Gough, M. Managing ash from municipal waste incinerators, in *Resources for the Future* (Washington, DC: Center for Risk Management, 1989); and U.S. Environmental Protection Agency. *2008 U.S. Waste Generation Before Recycling.* www.epa.gov.

Solid Waste Disposal

Disposal of solid waste is primarily an urban problem. Figure 19.6 summarizes major sources and types of solid waste, and Table 19.3 lists the generalized composition of solid waste (by weight, before recycling) in 1986 and 2008. We emphasize that this is only an average composition, and considerable variation can be expected because of differences in such

factors as land use, economic base, industrial activity, climate, and season of the year. It is no surprise that paper is by far the most abundant solid waste. Plastics have increased by about 70 percent since 1986, with a tremendous increase in plastic containers, such as bottles. All this plastic is not going unnoticed. There is an emerging industry involved in recycling waste plastic. Plastic recycling plants are being constructed and operated to handle many types of plastic. What was waste plastic is being recycled into new plastic, which is as good as that newly made from oil. Research is also underway to recycle plastic back into oil.

In some areas, infectious waste from hospitals and clinics can create problems if it is not properly sterilized before disposal. Some hospitals have facilities to incinerate such waste. In large urban areas, huge quantities of toxic materials may also end up at disposal sites. Urban landfills are now being considered hazardous waste sites that will require costly monitoring and cleanup.

Common methods of solid waste disposal include onsite disposal, composting, incineration, open dumps, and sanitary landfills.[39] Our focus here will be on the sanitary landfills because they are very common and have significant links with geology and hydrology.

A **sanitary landfill** (also called a *municipal solid waste landfill*), as defined by the American Society of Civil Engineering, is a method of solid waste disposal that functions without creating a nuisance or hazard to public health or safety. Engineering principles are used to confine the waste to the smallest practical area, reduce it to the smallest practical volume, and cover it with a layer of compacted soil or specially designed tarps at the end of each day of operation or more frequently, if necessary. It is this covering of the waste that makes a sanitary landfill sanitary. The cover effectively denies continued access to the waste by insects, rodents, and other animals, and it also isolates the refuse from the air. The use of the cover minimizes the amount of surface water entering into the waste and the amount of gas escaping from it.[40]

The sanitary landfill, as we know it today, emerged in the late 1930s. Two types are used: area landfills on relatively flat sites and depression landfills in natural or artificial gullies or pits. Normally, refuse is compacted and covered at the end of each day. The finishing cover (cap) or soil (clay) is designed to minimize the infiltration of surface water.[39]

Potential Hazards. One of the most significant potential hazards from a sanitary landfill is groundwater or surface-water pollution. When waste, buried in a landfill, comes in contact with water percolating down from the surface or with groundwater moving laterally through the refuse, *leachate* (obnoxious, toxic liquid of variable composition capable of transporting suspended solids and bacterial pollutants) is produced.[41] For example, two landfills dating from the 1930s and 1940s in Long Island, New York, have produced leachate plumes that are several hundred meters wide and have migrated several kilometers from the disposal site. Both the nature and the strength of leachate produced at a disposal site depend on the composition of the waste, the length of time that the infiltrated water is in contact with the refuse, and the amount of water that infiltrates or moves through the waste.[39] The concentration of pollutants in landfill leachate may be much higher than in raw sewage or slaughterhouse waste. Fortunately, the volume of leachate produced from urban waste disposal is much less than the volume of raw sewage we generate.

Another possible hazard from landfills is uncontrolled production and escape of methane gas, which is generated as organic waste decomposes. For example, gas generated in an Ohio landfill migrated several hundred meters through sandy soil to a housing area, where one home exploded and several others had to be evacuated. Properly managed, methane gas (if not polluted with toxic materials) is a resource. At new and expanded landfills, methane is often confined by barriers made of plastic liner and clay and then collected in specially constructed wells. The technology for managing methane is well known and available, and numerous landfills across the country are now producing methane and burning it to produce electricity or heat to reduce energy costs associated with waste management.

Site Selection. Factors controlling the feasibility of sanitary landfills include:

- Topographic relief
- Location of the groundwater table
- Amount of precipitation
- Type of soil and rock
- Location of the disposal zone in the surface-water and groundwater flow system

The best sites are those where natural conditions ensure reasonable safety in disposal of solid waste. This means that there is little (or acceptable) pollution of groundwater or surface water and that conditions are safe because of climatic, hydrologic, geologic, or human-induced conditions or combinations thereof.[42]

The best sites for landfills are in arid regions. Disposal conditions are relatively safe there because, in a dry environment, regardless of whether the burial material is permeable or impermeable, little or no leachate is produced. On the other hand, some leachate will always be produced in a humid environment, so an acceptable level of leachate production must be established to determine the most favorable sites. What is acceptable varies with local water use, local regulations, and the ability of the natural hydrologic system to disperse, dilute, and otherwise degrade the leachate to a harmless state.

The most desirable site in a humid climate is one in which the waste is buried above the water table in clay and silt soils of low hydraulic conductivity. Any leachate produced will remain in the vicinity of the site, where it will be degraded by natural filtering and by exchange of some ions between the clay and the leachate. This holds—even if the water table is fairly high, as it often is in humid areas—as long as material with low hydraulic conductivity is present.[39] For example, if the refuse is buried over a fractured rock aquifer, as shown in **Figure 19.7**, the potential for serious pollution is low to moderate because the leachate is partly degraded by natural filtering as it moves down to the water table. Furthermore, the dispersion of contaminants is confined to the fracture zones.[39] However, if the water table were higher, or if the cover material were thinner, with a moderate to high hydraulic conductivity, widespread groundwater pollution of the fractured rock aquifer might result.

If a landfill site is characterized by an inclined limestone rock aquifer covered by sand and gravel with high hydraulic conductivity (**Figure 19.8**), considerable contamination of the groundwater could result. Leachate moves quickly through the sand and gravel soil and enters the limestone, where open fractures or cavities may transport the pollutants with little degradation aside from dispersion and dilution. Of course, if the inclined rock is all shale with low hydraulic conductivity, little pollution will result.

The following general considerations[43] should be kept in mind in site selection for sanitary landfills:

- Limestone or highly fractured rock quarries and most sand and gravel pits make poor landfill sites because these Earth materials are good aquifers.
- Swampy areas, unless properly drained to prevent disposal into standing water, make poor sites.
- Floodplains likely to be periodically inundated by surface water should not be considered as acceptable sites for refuse disposal.

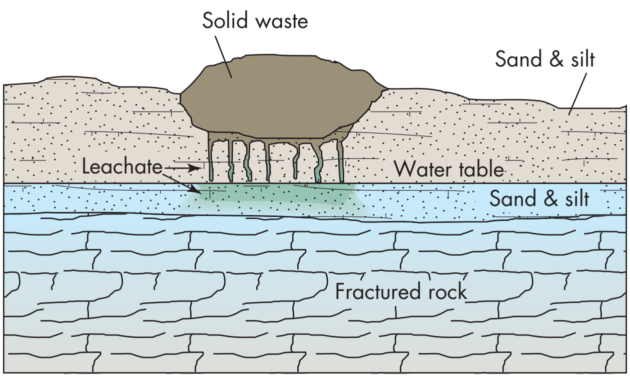


FIGURE 19.7 Solid waste disposal Site where refuse is buried above the water table over a fractured-rock aquifer. Potential for serious pollution is low to moderate because leachate is partially degraded by natural filtering as it moves down to the water table. *(After Schneider, W. J. 1970. U.S. Geological Survey Circular 601F)*

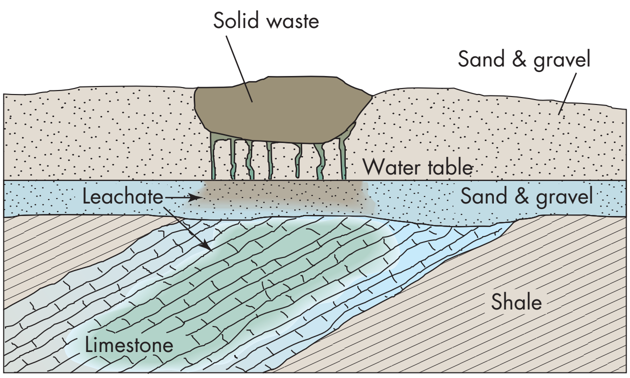


FIGURE 19.8 Solid-waste disposal Site where waste is buried. Leachate can migrate down to fractured bedrock (e.g., limestone). The potential for groundwater pollution is high because of the many open and connected fractures in the rock. *(After Schneider, W. J. 1970. U.S. Geological Survey Circular 601F)*

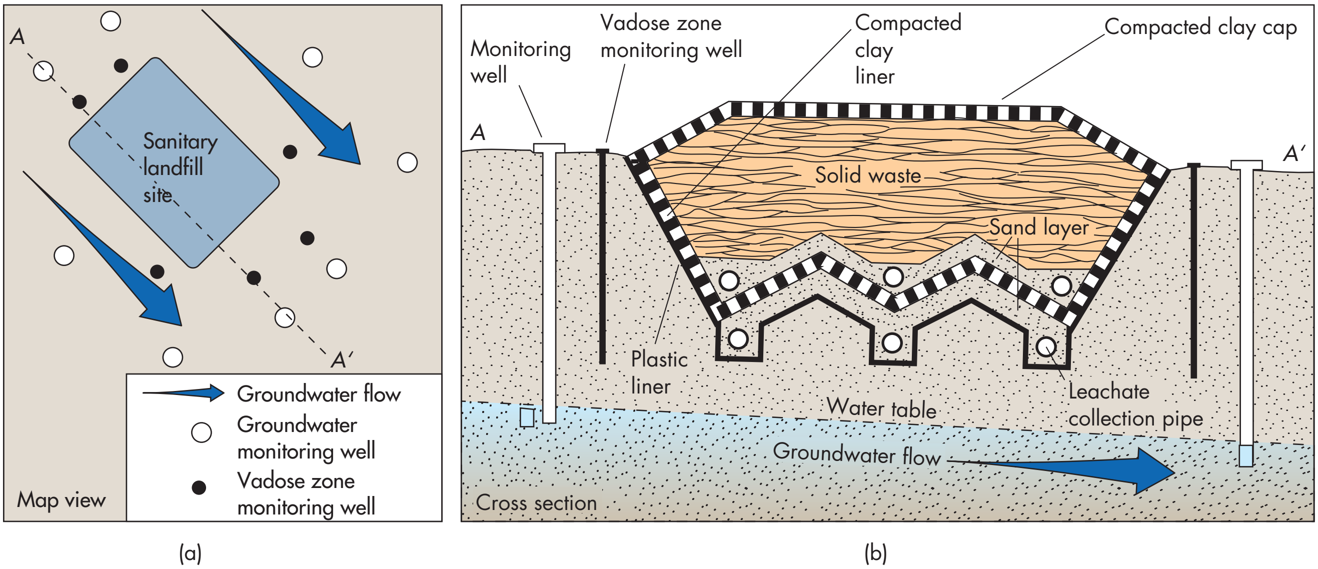


FIGURE 19.9 Landfill design Idealized diagrams showing map view (a) and cross section (b) of a landfill with a double liner of clay and plastic and a leachate collection system.

- Areas in close proximity to the coast—where trash (transported by wind or surface water) or leachate in groundwater or surface water may pollute beaches and coastal marine waters—are undesirable sites.
- Any material with high hydraulic conductivity and with a high water table is probably an unfavorable site.
- In rough topography, the best sites are near the heads of gullies, where surface water is at a minimum.
- Clay pits, if kept dry, provide satisfactory sites.
- Flat areas are favorable sites, provided that an adequate layer of material with low hydraulic conductivity, such as clay and silt, is present above any aquifer.

We emphasize that, although these guidelines are useful, they do not preclude the need for a hydrogeological investigation that includes drilling to obtain samples, permeability testing to determine hydraulic conductivity, and other tests to predict the movement of leachate from the buried refuse.[40]

Design of Sanitary Landfills. Design of modern sanitary landfills for municipal solid waste (MSW) is complex and employs the multiple-barrier approach. Barriers include a compacted clay liner, leachate collection systems, and a compacted clay

FIGURE 19.10 Rock Creek municipal landfill This municipal landfill in Calaveras County, California, is under construction. The light brown slope in the central part of the photograph is a compacted clay liner. The sinuous ditch is part of the leachate collection system, and the square pond in the upper part of the photograph is the leachate evaporation pond under construction. *(Courtesy of John Kramer/ California Integrated Waste Management Board)*

cap. Figure 19.9 is an idealized diagram showing these features, and Figure 19.10 shows such a landfill being constructed. Depending upon local site conditions, landfills may also have additional synthetic liners made of plastics or other materials and a system to collect natural gas that might accumulate. Finally, a sanitary landfill must have a system for monitoring wells and other devices to evaluate the potential for groundwater pollution. The subject of

monitoring is an important one, and we will now address that issue in greater detail.

Monitoring Sanitary Landfills. Once a site is chosen for a sanitary landfill, **monitoring** the movement of groundwater should begin before filling commences. After the operation starts, monitoring of the movement of leachate and gases should be continued as long as there is any possibility of pollution. This is particularly important after the site is completely filled and the permanent cover material is in place because a certain amount of settlement always occurs after a landfill is completed. If small depressions form as a result of settlement, surface water can collect, infiltrate the fill material, and produce leachate. Therefore, monitoring and proper maintenance of an abandoned landfill will reduce its pollution potential.[40]

Hazardous waste pollutants from a solid waste disposal site can enter the environment by as many as seven paths (**Figure 19.11**):[44]

1. Gases in the soil and fill, such as methane, ammonia, hydrogen sulfide, and nitrogen, may volatilize and enter the atmosphere.
2. Heavy metals, such as lead, chromium, and iron, are retained in the soil.
3. Soluble substances, such as chloride, nitrate, and sulfate, readily pass through fill and soil to the groundwater system.
4. Surface runoff can pick up leachate and transport it into the surface water network.
5. Some crops and cover plants growing in the disposal area may selectively take up heavy metals and other toxic substances to be passed up the food chain as people and animals ingest them.
6. Plant residue left in the field contains toxic substances that will return to the environment through soil-forming and runoff processes.
7. Paper, plastics, and other undesirable waste may be transported offsite by wind.

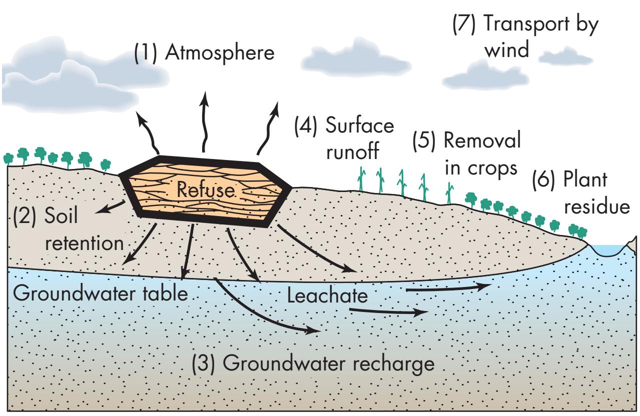


FIGURE 19.11 Several ways that hazardous waste pollutants from a solid waste disposal site may enter the environment.

A thorough monitoring program considers these seven possible paths by which pollutants enter the environment. Potential atmospheric pollution by gas from landfills is a growing concern, and a thorough monitoring program includes periodic analysis of air samples to detect toxic gas before it becomes a serious problem. Many landfills have no surface runoff; therefore, monitoring onsite surface water is not necessary. However, if surface runoff does occur, thorough monitoring is required, as well as monitoring of nearby down-gradient streams, rivers, and lakes. Monitoring of soil and plants should include periodic chemical analysis at prescribed sampling locations.

If permeable water-bearing zones exist in the soil or bedrock below a sanitary landfill, monitoring wells (see Figure 19.9) are needed for frequent sampling of groundwater quality and monitoring of the movement of any leachate that has entered the groundwater.[44] Even if the landfill is in relatively impermeable soil overlying dense permeable rock, minimal monitoring of groundwater quality through monitoring wells is still needed. In this case, leachate and groundwater movement may be less than 30 cm per year. Water in the unsaturated (vadose) zone above the water table must also be monitored to identify potential pollution problems before they contaminate groundwater resources, where correction is very expensive. Waste transported offsite by wind must be monitored, collected as necessary, and disposed of.

Sanitary Landfills and Federal Legislation. Federal legislation strictly regulates new landfills. The intent of the legislation is to strengthen and standardize the design, operation, and monitoring of sanitary landfills. Landfills that are unable to comply with the regulations might be shut down. Specific regulations include:

- Landfills cannot be sited in certain areas, including floodplains, wetlands, unstable land, and earthquake fault zones. They must not be sited near airports because birds attracted to landfill sites present a hazard to aircraft.
- Landfill construction must include liners and a leachate collection system.

TABLE 19.4 Examples of Materials We Use and Potentially Hazardous Waste They Generate

Materials	Potential Hazardous Waste
Plastics	Organic chlorine compounds
Pesticides	Organic chlorine compounds, organic phosphate compounds
Medicines	Organic solvents and residues, heavy metals (e.g., mercury and zinc)
Paints	Heavy metals, pigments, solvents, organic residues
Oil, gasoline, and other petroleum products	Oil, phenols and other organic compounds, heavy metals, ammonia salts, acids, caustics
Metals	Heavy metals, fluorides, cyanides, acid and alkaline cleaners, solvents, pigments, abrasives, plating salts, oils, phenols
Leather	Heavy metals, organic solvents
Textiles	Heavy metals, dyes, organic chlorine compounds, solvents

U.S. Environmental Protection Agency. SW-826, 1980.

- Operators of landfills must monitor groundwater for specific toxic chemicals.
- Operators of landfills must meet financial assurance criteria. They do so by posting bonds or insurance to ensure that monitoring of the landfill continues for 30 years after closure.

Hazardous Waste Management

The creation of new chemical compounds has proliferated tremendously in recent years. In the United States alone, approximately 1,000 new chemicals are marketed annually, and about 50,000 chemicals are currently on the market. Although many of these chemicals are beneficial to people, several tens of thousands of them are classified as definitely or potentially hazardous to people's health (**Table 19.4**).

The United States is currently generating more than 150 million metric tons of **hazardous waste** each year. In the recent past, as much as half of the total volume of waste was dumped indiscriminately.[45] Such dumping is now illegal, and we do not know how much illegal dumping is going on; certainly there is some, particularly in urban sewer systems. Past uncontrolled dumping of chemical waste has polluted soil and groundwater resources in several ways (**Figure 19.12**):

- Barrels in which chemical waste is stored, either on the surface or buried at a disposal site, eventually corroded and leaked, polluting the surface, soil, and groundwater.
- Liquid chemical waste dumped in unlined lagoons (i.e., shallow ponds for collection of waste) has percolated through the soil and rock and eventually reached the groundwater table.
- Liquid chemical waste has been illegally dumped in deserted fields or along dirt roads.
- E-waste, such as computers, TVs, and the like, is being sent to foreign countries, such as China, where it is exposing workers to toxic components.

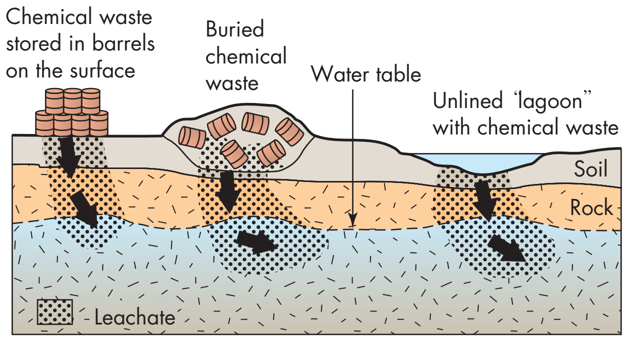


FIGURE 19.12 Ways that uncontrolled dumping of chemical waste may pollute soil and/or groundwater.

Old abandoned hazardous landfills and other sites for the disposal of chemical waste have caused serious problems that have been very difficult to correct (see A Closer Look: Love Canal).

A Closer Look

Love Canal

In 1976, in a residential area near Niagara Falls, New York, trees and gardens began to die. Children found the rubber on their tennis shoes and on their bicycle tires disintegrating. Dogs sniffing in a landfill area developed sores that would not heal. Puddles of toxic, noxious substances began to ooze to the soil surface; a swimming pool popped its foundation and was found to be floating on a bath of chemicals.

A study revealed that the residential area had been built on the site of a chemical dump. The area was excavated in 1892 by William T. Love as part of a canal between the upper and lower reaches of the Niagara River. The idea was to produce inexpensive hydroelectric power for a new urban industrial center. When that plan failed because alternating current was discovered and industry could be located far from the source of power, the canal was unused (except for recreation, such as swimming and ice skating) for decades. It seemed a convenient place to dump wastes. From the 1940s to the 1950s, more than 80 different substances from a chemical company were dumped there. More than 20,000 tons of chemical waste, along with urban waste from the city of Niagara Falls, was disposed of in the canal.[46] Finally, in 1953, the company dumping the chemicals donated the land to the city of Niagara Falls for $1. Eventually, several hundred homes adjacent to an elementary school were built near the site (**Figure 19.D**). Heavy rainfall and snowfall during the winter of 1976–1977 set off the chain of events that made Love Canal a household word.

A study of the site identified a number of substances present there—including benzene, dioxin, dichloroethylene, and chloroform—that were suspected of being carcinogens. Although officials readily admitted that very little was known

FIGURE 19.D Love Canal This is an infrared aerial photograph of the Love Canal area in New York. Healthy vegetation is bright red. This portion of Love Canal runs from the upper-left corner to the lower-right corner. It appears as a scar on the landscape. Buried chemical waste seeped to the surface and caused numerous environmental problems and concerns. The site became a household name for toxic waste. *(New York State Department of Environmental Conservation)*

about the impact of these chemicals and others at the site, there was grave concern for the people living in the area. During the next few years, there were, allegedly, higher-than-average rates of miscarriages, blood and liver abnormalities, birth defects, and chromosome damage. However, a study by the New York State health authorities suggested that no chemically caused health effects had been absolutely established.[47–49]

The cleanup of the Love Canal is an important demonstration of state-of-the-art technology in hazardous waste treatment. The objective is to contain and stop the migration of waste through the groundwater flow system and to remove and treat dioxin-contaminated soil and sediment from stream beds and storm sewers.[46] The method being used to minimize further production of contaminated water is to cover the dump site and the adjacent contaminated area with a 1 m-thick layer of compacted clay and a polyethylene plastic cover to reduce infiltration of surface water. Water is inhibited from laterally entering or escaping the site by specially designed perforated tile drain pipes. These procedures will greatly reduce subsurface seepage of water through the site, and the water that does seep out will be collected and treated.[47–49]

The homes adjacent to Love Canal were abandoned and bought by the government. Approximately 200 of the homes had to be destroyed. During the 1980s, approximately $175 million was spent for cleanup and relocation at Love Canal. The EPA now considers some of the area clean, and some of the remaining homes (about 200) were sold. They sold despite the reputation of the area and the adverse publicity it attracted because the price of the homes was approximately 20 percent below the market value of other areas in Niagara Falls. The neighborhood is now known as Black Creek Village. In early 1995, the maintenance and operation of the area was transferred from New York State to a consulting company, which will continue long-term sampling and monitoring.[46,50] Also, in 1995, the Occidental Chemical Company agreed to pay $129 million to cover the cost of the incident.

What went wrong in Love Canal? How can we avoid such disasters in the future? The real tragedy of Love Canal is that it is probably not an isolated incident. There may be other hidden "Love Canals" across the country, "time bombs" waiting to explode.[47,48]

Responsible Management of Hazardous Waste. In 1976, the U.S. government moved to begin the management of hazardous waste with the passage of the Resource Conservation and Recovery Act (RCRA), which is intended to provide for "cradle-to-grave" control of hazardous waste. At the heart of the act is the identification of hazardous wastes and their life cycles. Regulations call for stringent record keeping and reporting to verify that waste does not present a public nuisance or a public health problem. The act also identifies hazardous waste in terms of several categories:

- Waste that is highly toxic to people and other living things
- Waste that may explode or ignite when exposed to air
- Waste that is extremely corrosive
- Waste that is otherwise unstable

Recognizing that a great number of waste disposal sites presented hazards, Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in 1980, which established a revolving fund (popularly called the *Superfund*) to clean up several hundred of the worst abandoned hazardous chemical waste disposal sites known to exist around the country. The EPA developed a list of Superfund sites (i.e., the National Priorities List). Most of the Superfund sites (about 50 to 75 percent) significantly impact groundwater resources, drinking water, and surface water, in some combination. Fewer sites (10 to 25 percent) directly and seriously impact air resources, vegetation, animal life, or human health.

Although the Superfund has experienced significant management problems and is far behind schedule, a number of sites have been treated. Unfortunately, the funds available are not sufficient to pay for decontamination of all the targeted areas. That would cost many times more, perhaps as much as $100 billion. Furthermore, because of concern that the present technology is not sufficiently advanced to treat all the abandoned waste disposal sites, the strategy may be simply to confine the waste to those areas until better disposal methods are developed. It seems apparent that the danger of abandoned disposal sites is likely to persist for some time to come.

The federal legislation also changed the way the real estate industry does business. The act has tough liability provisions, and property owners could be liable for costly cleanup of hazardous waste found on their property (even if they did not cause the problem). Banks and other lending institutions could be liable for release of hazardous materials on their property by their tenants. In 1986, the Superfund Amendments and Reauthorization Act (SARA) provided a possible defense for real estate purchasers against liability, provided that they completed an *environmental audit* prior to purchase. The audit is a study of past land use at the site (determined by analyzing old maps and aerial photographs, possibly involving drilling and sampling of soil and groundwater) to determine whether pollutants are present. Such audits now are done routinely prior to purchase of property for development.

The SARA legislation required that certain industries report all releases of hazardous materials into the environment. The list of companies releasing such substances became public and was known as the "Toxic 500 list." Unwanted publicity to companies on the list is thought to have resulted in better and safer handling of hazardous waste by firms that were formerly identified as polluters of the environment. No owner wants his or her company to be the "number one" (or even the twenty-fifth or hundredth) most serious polluter among U.S. firms.[51]

Management of hazardous chemical waste includes several options: recycling (onsite processing to recover by-products that have commercial value), microbial breakdown, chemical stabilization, high-temperature decomposition, incineration, and disposal by secure landfill or deep-well injection. A number of technological advances have been made in the field of toxic waste management, and, as land disposal becomes more and more expensive, the recent trend toward onsite treatment is likely to continue. However, onsite treatment will not eliminate all hazardous chemical waste; disposal will remain necessary. **Table 19.5** compares hazardous waste-reduction technology in terms of treatment and disposal. Notice that all of the technologies available will cause some environmental disruption. No one simple solution exists for all waste-management issues. We will discuss the secure landfill land application and deep well disposal that have important linkages to geology and hydrology. Other options include the reuse of hazardous materials and treatment of hazardous waste to reduce the hazardous characteristics.

Secure Landfill for Hazardous Waste. The basic idea of a **secure landfill** is to confine waste to a particular location, control the leachate that drains from the waste, collect and treat the leachate, and detect possible leaks. **Figure 19.13** (page 692) demonstrates these procedures. A dike and liners (made of clay and impervious material, such as plastic) confine the waste, and a system of internal drains concentrates the leachate in a collection basin, from which it is pumped out and transported to a wastewater treatment plant. Designs of new facilities today must include multiple barriers, consisting of several impermeable layers and filters, as well as impervious covers. The function of impervious liners is to ensure that the leachate does not contaminate soil and, in particular, groundwater resources. However, this type of waste disposal procedure must have several monitoring wells to alert personnel if leachate migrates out of the system, possibly contaminating nearby water resources.

It has been argued that there is no such thing as a really secure landfill, implying that all landfills leak to some extent. This is probably true; impervious plastic liners, filters, and clay layers can fail, even with several backups, and drains can become clogged, causing overflow. Yet, landfills that are carefully sited and engineered can minimize problems. Preferable sites are those with good natural barriers, such as thick clay-silt deposits, an arid climate, or a deep water table that minimizes migration of leachate. Nevertheless, land disposal should be used only for specific chemicals suitable for the method employed.

Land Application

Application of waste materials to the surface-soil horizon is referred to as *land application*, *land spreading*, or *land farming*. Land application may be a desirable treatment method for certain biodegradable industrial wastes, including petroleum oily waste and certain organic chemical-plant waste. A good indicator of the usefulness of land application for disposal of a particular waste is the waste's *biopersistence* (i.e., the measure of how long

TABLE 19.5 Comparison of Hazardous Waste–Reduction Technologies

	Disposal		Treatment		
	Landfills and Impoundments	Injection Wells	Incineration and Other Thermal Destruction	Emerging High-Temperature Decomposition[1]	Chemical Stabilization
Effectiveness: How well it contains or destroys hazardous characteristics	Low for volatiles, questionable for liquids; based on lab and field tests	High based on theory, but limited field data available	High based on field data, but little data on specific constituents	Very high; commercial-scale tests	High for many metals based on lab tests
Reliability issues	Siting, construction, and operation Uncertainties: long-term integrity of cells and cover, liner life less than life of toxic waste	Site history and geology; well depth, construction, and operation	Monitoring uncertainties with respect to high degree of DRE: surrogate measures, PICs, incinerability[3]	Limited experience Mobile units, onsite treatment avoids hauling risks Operational simplicity	Some inorganics still soluble Uncertain leachate test, surrogate for weathering
Environmental media most affected	Surface and groundwater	Surface and groundwater	Air	Air	Groundwater
Least compatible wastes[2]	Liner reactive, highly toxic, mobile, persistent, and bioaccumulative	Reactive; corrosive; highly toxic, mobile, and persistent	Highly toxic and refractory organics, high heavy metals concentration	Some inorganics	Organics
Relative costs: low (L), moderate (M), high (H)	L–M	L	M–H	M–H	M
Resource recovery potential	None	None	Energy and some acids	Energy and some metals	Possible building material

[1]Molten salt, high-temperature fluid well, and plasma arc treatments.

[2]Relative to other technologies, this method is less effective for reducing waste exposure.

[3]DRE = destruction and removal efficiency; PIC = product of incomplete combustion.

Council on Environmental Quality, 1983.

a material remains in the biosphere). The greater or longer the biopersistence, the less suitable the waste is for land-application procedures. Land application is not an effective treatment or disposal method for inorganic substances, such as salts and heavy metals.[52]

Land application of biodegradable waste works because, when such materials are added to the soil, they are attacked by microorganisms (e.g., bacteria, molds, yeast, other organisms) that decompose the waste material. The soil may, thus, be thought of as a microbial farm that constantly recycles matter by breaking it down into more fundamental forms useful to other living things in the soil. Because the upper soil zone contains the largest microbial populations, land application is restricted to the uppermost 15 to 20 cm of the soil profile.[52] As with other types of land-disposal technology, the vadose zone and groundwater near the site must be carefully monitored to ensure that the disposal system is working as planned and not polluting water resources.

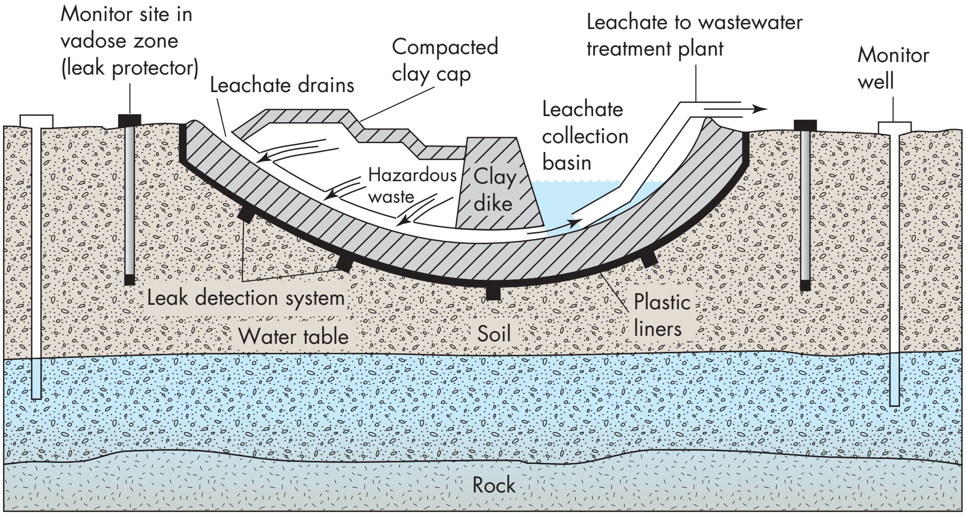


FIGURE 19.13 Secure landfill for hazardous chemical waste The impervious liners and systems of drains are an integral part of the system to ensure that leachate does not escape the disposal site. Monitoring in the vadose zone is important and involves periodic collection of soil water with a suction device.

Deep-Well Disposal

Another method of hazardous waste disposal is injection into deep wells. The term *deep* refers to rock (not soil) that is below and completely isolated from all freshwater aquifers, thereby ensuring that injection of waste will not contaminate or pollute existing or potential water supplies. This generally means that the waste is injected into a permeable rock layer several hundred to several thousand meters below the surface, in geologic basins that are confined above by relatively impervious, fracture-resistant rock, such as shale or salt deposits.[53]

Deep-well disposal of industrial waste should not be viewed as a quick-and-easy solution to industrial waste problems.[54] Even where geologic conditions are favorable for deep-well disposal, natural restrictions include the limited number of suitable sites and the limited space within these sites for disposal of waste. Possible injection zones in porous rock are usually already filled with natural fluids, mostly brackish or briny water. Therefore, to pump in waste, some of the natural fluid must be displaced by compression (even slight compression of the natural fluids in a large volume of permeable rock can provide considerable storage space) and by slight expansion of the reservoir rock as the waste is being injected.[55]

Problems with Deep-Well Disposal. Several problems associated with disposal of liquid waste in deep wells have been reported.[54,55] Perhaps the best known are the earthquakes that were caused by injecting waste from the Rocky Mountain Arsenal near Denver, Colorado (see Chapter 6). These earthquakes occurred between 1962 and 1965. The injection zone was fractured gneiss at a depth of 3.6 km, and the increased fluid pressure evidently initiated movement along the fractures. This is not a unique case. Similar initiations of earthquakes have been reported in oil fields in western Colorado, Texas, and Utah.[55]

Feasibility and General Site Considerations. The feasibility of deep-well injection as the best solution to a disposal problem depends on four factors: (1) the geologic and engineering suitability of the proposed site, (2) the volume and the physical and chemical properties of the waste, (3) economics, and (4) legal considerations. The geologic considerations for disposal wells are twofold:[55]

- The injection zone must have sufficient porosity, thickness, hydraulic conductivity, and size to ensure safe injection. Sandstone and fractured limestone are the commonly used reservoir rocks.
- The injection zone must be below the level of freshwater circulation and confined by a relatively impermeable rock with low hydraulic conductivity, such as shale or salt, as shown in Figure 19.14.

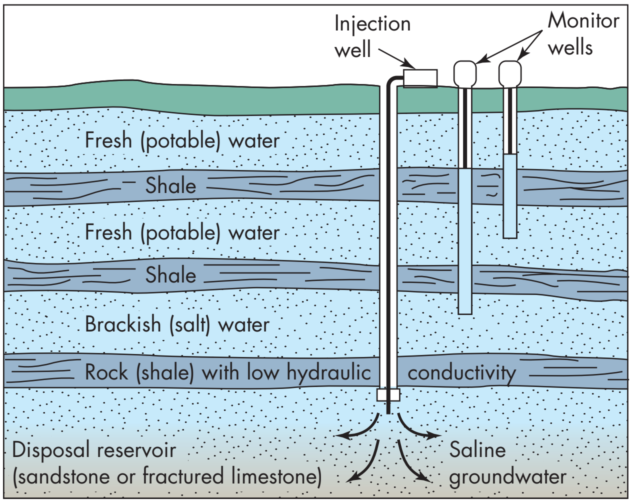


FIGURE 19.14 Deep-well injection system The disposal reservoir is in sandstone or fractured limestone, capped by impermeable rock and isolated from all freshwater. Monitor wells are a safety precaution taken to ensure that there is no undesirable migration of the liquid waste into freshwater aquifers above the injection zone.

19.5 Environmental Analysis

Site Selection

Site selection is the process of evaluating an environment that will support human activities. It is a task shared by Earth scientists, engineers, landscape architects, geographers, ecologists, planners, social scientists, and economists and, thus, involves a multidimensional approach to landscape evaluation.

The goal of site evaluation for a particular land use is to ensure that site development is compatible with both the possibilities and the limitations of the natural environment. Although it is obviously advantageous to know the possibilities and limitations of a site before development begins, site evaluation is often overlooked. People still purchase land for various activities without considering whether the land use they have in mind is compatible with the site they have chosen.

An Earth scientist plays a significant role in the evaluation process by providing crucial geologic information. This information includes soil and rock types; rock structure, especially fractures; drainage characteristics; groundwater characteristics; landform information; and estimates of possible hazardous Earth events and processes, such as floods, landslides, earthquakes, and volcanic activity. An engineering geologist also takes samples, makes tests, and predicts the engineering properties of Earth materials.

Environmental Impact Analysis

The probable effects of land use by humans are generally referred to as the *environmental impact*. This term became popular in 1969, when the National Environmental Policy Act (NEPA) required that every major federal action that could possibly affect the quality of the human environment be preceded by an evaluation of the project and its impact on the environment.

Environmental Impact Statements

To carry out both the letter and the spirit of NEPA, the Council on Environmental Quality prepared guidelines to help in preparing the **environmental impact statement (EIS)**. The major components of the statement, according to the revised guidelines issued in 1979, are the following:[56]

- A summary of the EIS
- A statement concerning the proposed acts, their purpose, and the need for the project
- A rigorous comparison of reasonable alternatives
- A succinct description of the environment affected by the proposed project
- A discussion of the proposed project, its environmental consequences, and alternatives. This must include direct and indirect effects; energy requirements and conservation potential; possible depletion of resources; impact on urban quality and cultural and/or historical resources; possible conflicts with state or local land-use plans, policies, and controls; and mitigation measures.

Scoping. The environmental impact statement process was criticized during the first 10 years under NEPA because it initiated a tremendous volume of paperwork by requiring detailed reports that tended to obscure important issues. In response, the revised regulations introduced the idea of **scoping**, the process of identifying important environmental issues that require detailed evaluation early in the planning of a proposed project. As part of this process, federal, state, and local agencies, as

well as citizen groups and individuals, are asked to participate by identifying issues and alternatives that should be addressed as part of the environmental analysis.

Mitigation. An important concept in an environmental impact analysis is **mitigation**. Mitigation involves identifying actions that will avoid, lessen, or compensate for anticipated adverse environmental impacts of a particular project. For example, if a project involves filling in wetlands, a possible mitigation might be enhancement or creation of wetlands at another site.

Mitigation is becoming a common feature of many environmental impact statements and state environmental impact reports. Unfortunately, it may be overused. Sometimes mitigation is not possible for a particular environmental disruption. Furthermore, we often do not know enough about restoring and creating habitats and environments, such as wetlands, to do a proper job. Requiring mitigation procedures may be useful in many instances, but it must not be considered an across-the-board, acceptable way to circumvent adverse environmental impacts associated with a particular project.

Negative Declarations

Negative declarations are filed when an agency determines that a particular project does not have a significant adverse impact on the environment. A negative declaration requires a statement that includes a description of the project and detailed information that supports the contention that the project will not have a significant effect on the environment. A negative declaration does not have to consider a wide variety of alternatives to the project, but it should be a complete and comprehensive statement concerning potential environmental problems.[57] Although the language and law associated with the concept of the negative declaration are different at the federal and state levels, this concept is an important component of environmental assessment.

Land Use and Planning

Land use in the contiguous United States is dominated by agriculture and forestry, with only a small portion of the land, approximately 3 percent, used for urban purposes. Currently, several thousand square kilometers of land per year are converted to uses other than agriculture. About one-half of the conversion is for wilderness areas, parks, recreation areas, and wildlife refuges. The other half is for urban development, transportation networks, and facilities. On a national scale, urbanization of rural lands may appear to be proceeding slowly. However, it often occurs in rapidly growing urban areas, where it may be viewed as destroying agricultural and natural lands and intensifying existing urban environmental problems. Urbanization in areas with scenic and recreation value is often viewed as potentially damaging to important ecosystems.

Land Use Planning

Land use planning is an important environmental issue. Good land use planning is essential for sound economic development, for avoiding conflicts between land uses, and for maintaining a high quality of life in our communities. When a business manages its capital and resources in an efficient manner, we call that good business. When a city or county efficiently manages its land and resources, we call that good planning.[58] From an Earth science perspective, the basic philosophy of good land-use planning is to avoid hazards, conserve natural resources, and generally protect the environment through the use of sound ecological principles.

The land use planning process shown in **Figure 19.15** includes several steps:[59]

- Identify and define issues, problems, goals, and objectives
- Collect, analyze, and interpret data (including an inventory of environmental resources and hazards)
- Develop and test alternatives
- Formulate land-use plans
- Review and adopt plans
- Implement plans
- Revise and amend plans

The three most important steps, each of which comprises a complex list of factors, are data collection, formulation of plans, and implementation of plans, as illustrated in Figure 19.15 (lower part).

The role of an Earth scientist in the planning process is most significant in the data collection and analysis stage. Depending on the specific task or

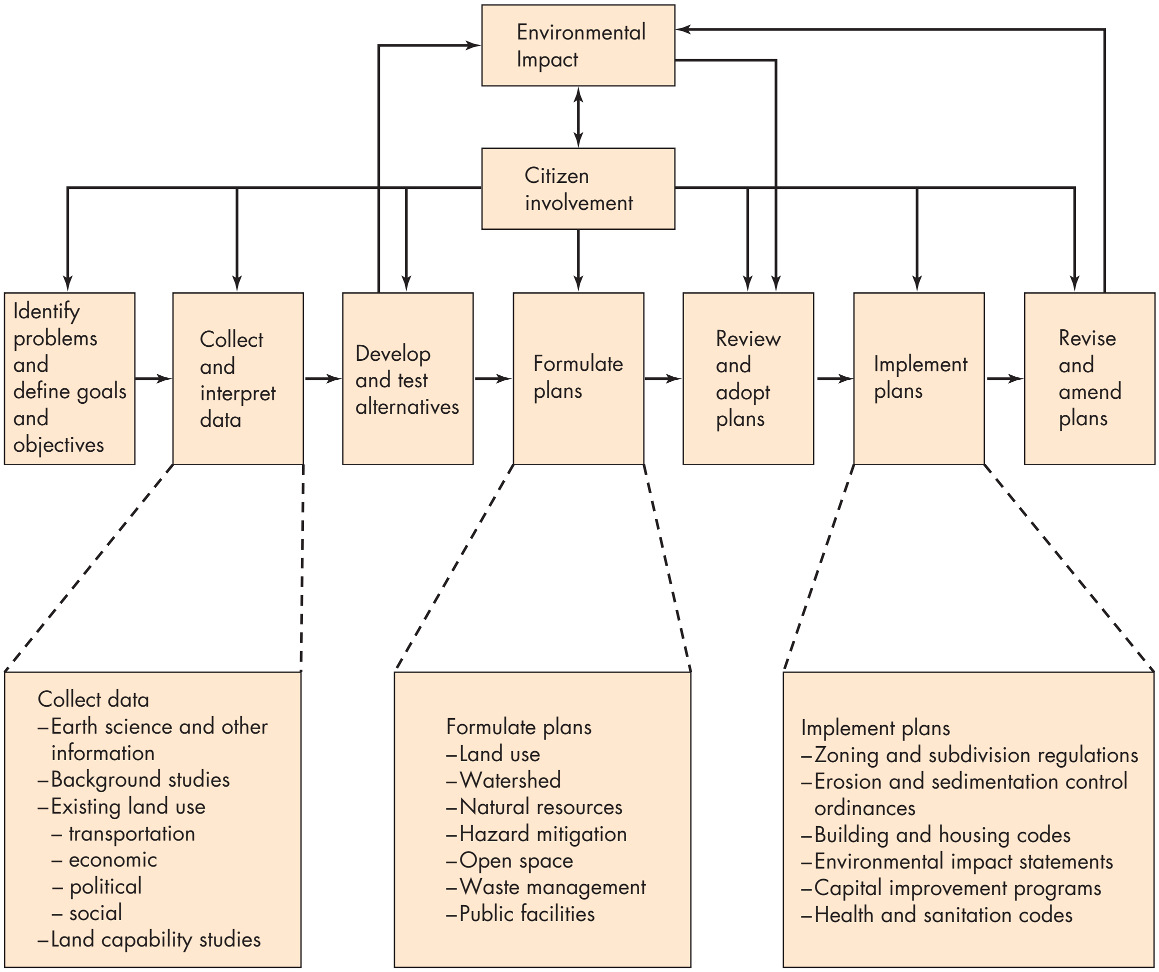


FIGURE 19.15 The land use planning process *(Modified after U.S. Geological Survey Circular 721, 1976)*

plan, an Earth scientist will use available Earth science information; collect necessary new data; prepare pertinent technical information, such as interpretive maps and texts; and assist in the preparation of land-capability maps. Ideally, the natural capability of a land unit should match its specific potential uses.[60]

Scenic Resources

Scenery in the United States has been recognized as a natural resource since 1864, when the first state park, Yosemite Valley in California, which later became Yosemite National Park, was established. The early recognition of scenic resources was primarily concerned with outdoor recreation, focusing on preservation and management of discrete parcels of unique scenic landscapes. Public awareness of and concern for the scenic value of the "everyday" nonurban landscape is relatively recent. Society now fully recognizes scenery—even when it is not spectacular—as a valuable resource. There is now awareness that landscapes have varying degrees of scenic value, just as more tangible resources have varying degrees of economic value. Earth scientists, as members of a team evaluating the entire environment, assist in characterization of the landscape and its resources, including scenery.

Sequential Land Use

The need to use land near urban areas for a variety of human activities has, in some instances, led to application of the concept of sequential land use rather than permanent, exclusive use. The concept of sequential use of the land is consistent with the principle that the effects of land use are cumulative, and, therefore, we have a responsibility to future generations. The basic idea is that, after a particular activity,

(a)

(b)

FIGURE 19.16 Sequential land use at Little Traverse Bay, Lake Michigan Near Petoskey, Michigan, an abandoned quarry and cement plant (a) were transformed into a world-class resort (b). (Note quarry wall behind the plant and small building right of the access road.) *([a] Ned Tanner; [b] Ned Tanner)*

such as mining or a landfill operation, has been completed, the land is reclaimed for another purpose.

There are several examples of sequential land use. Sanitary landfill sites have been planned so that, when a site is completed, the land will be used for recreational purposes, such as a golf course. The city of Denver used abandoned sand and gravel pits once used for a sanitary landfill as sites for a parking lot and the Denver Coliseum. Bay Harbor, Michigan, is a modern upscale community and a world-class resort in Little Traverse Bay, near the north end of Lake Michigan. The harbor and other development resulted from restoration of an abandoned shale quarry and cement plant. The restoration transformed a site that was a source of cement dust, an air pollutant, into a high-value landscape that people wish to visit (**Figure 19.16**).

Multiple Land Use

Multiple land use occurs where land may be used for more than one purpose. For example, our national forests are used for a variety of purposes, including recreation and timber harvesting. Other examples include reservoirs designed for providing irrigation water, flood control, and recreation. It has often been said that it is difficult to maximize benefits for more than one purpose. This is certainly true for multiple land use. Recreation and timber harvesting are not compatible, if we wish to maximize both the number of trees harvested and the number and quality of fish in a forest stream. Logging, unless done very carefully, and with a wide buffer zone to protect the stream, will damage a stream environment (**Figure 19.17**). Damage may occur if we remove trees that provide shade for the stream and keep the water cool; damage may also occur through sediment pollution from increased runoff and soil erosion and through landsliding and the formation of gullies. Likewise, a reservoir designed to provide water for summer irrigation of farm land may be full in the spring, when flood protection is needed, and be very low, exposing the shorline to erosion, when people arrive for late summer recreation (**Figure 19.18**, page 698).

Environmental Law

Environmental planning needs to be implemented and enforced, and **environmental law** is, therefore, an important part of our jurisprudence. Environmental law is a maturing law practice and environmental law societies, and environmental courses have been established at law schools.

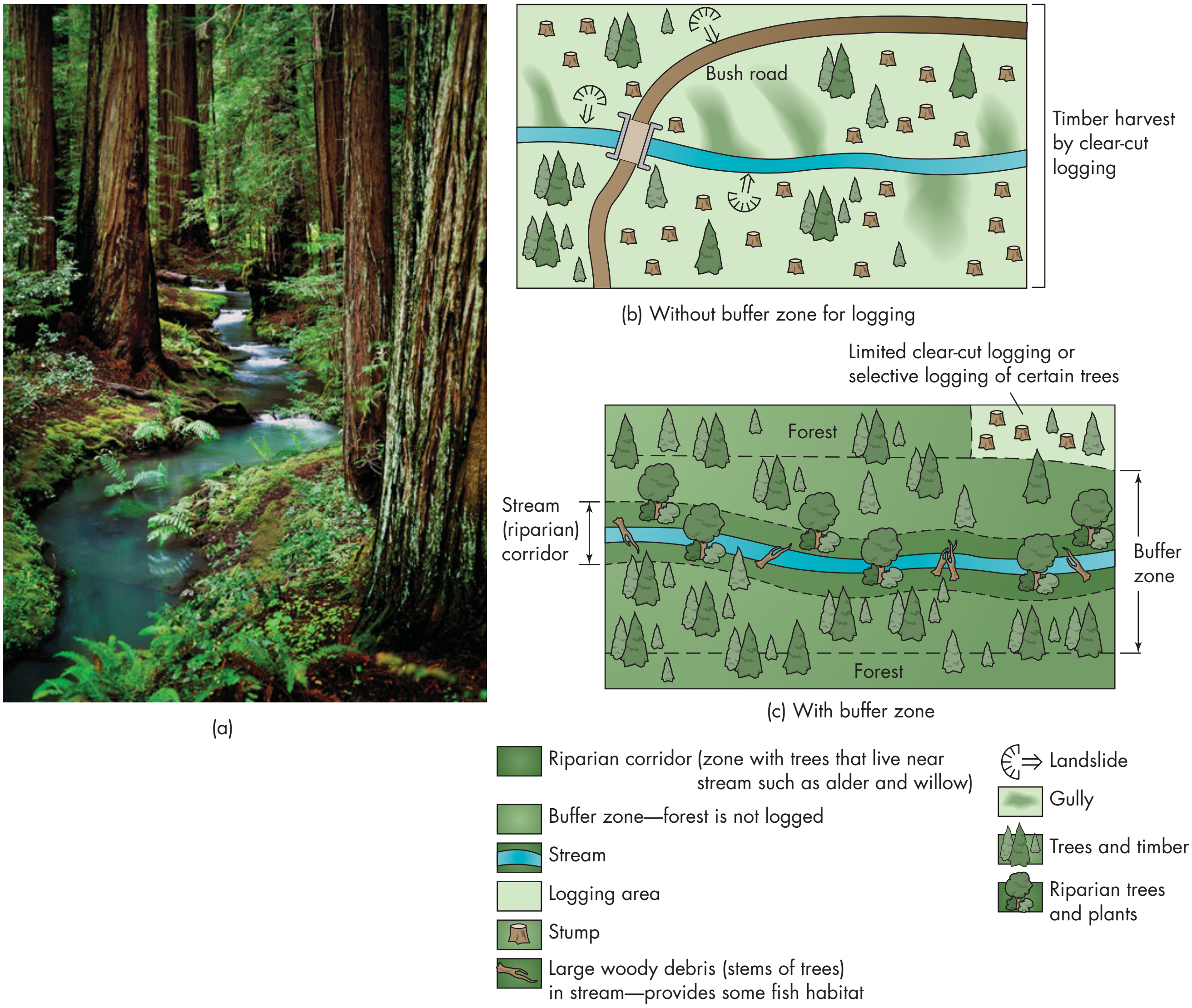


FIGURE 19.17 Timber harvesting and erosion (a) Stream in redwood forest of northwestern California. *(John Birchard/Alamy)* (b) Landsliding and gully erosion damage a forest stream when a wide buffer zone is not part of the plan to harvest timber. This type of damage is particularly common with clear-cut logging, which removes nearly all trees. (c) Timber harvest plan that leaves the stream area intact and has a wide buffer zone.

It is beyond the scope of our discussion to consider in detail the process of law as it relates to the environment. Suffice it to say that law is a technique for the ordered accomplishment of economic, social, and political purposes, and the most desirable legal technique, generally, is one that most quickly allows ends to be reached. Laws related to the environment often primarily serve the major interest that dominates the culture, and, in our sophisticated culture, the major concerns are wealth and power. These concerns stress society's ability to use the resource base to produce goods and services and a legal system to ensure productivity.[61] On the other hand, in recent years, many laws have been established to protect the air, water, land, and living environment at local, regional, and global levels. This is an encouraging sign, if we hope to sustain Earth's renewable resources.

Some environmental lawyers today believe that the process of law, as it has generally been practiced, is not working satisfactorily where environmental issues are concerned. In general, when two views

FIGURE 19.18 Exposed shoreline
Pontsticill Reservoir in Wales at low water. The exposed shoreline is not a pleasant setting for recreational activity. *(Chris Howes/ Wild Places/Alamy)*

conflict, adversarial confrontation occurs. Emotional levels are often high, and it may be difficult for disagreeing parties to see positions other than their own. An emerging view in environmental law is one that stresses problem solving. This may take the form of mediation through negotiation. For example, in the 1970s, the Environmental Protection Agency often announced new environmental regulations that were thrust upon various sectors of society without warning. Not surprisingly, many of the people and organizations affected by those regulations ended up in lawsuits and lengthy litigation. In the 1980s, the EPA began a practice of consulting interested parties before enacting regulations. Consultation, negotiation, and *mediation* may well prove much more successful than earlier strategies that produced unproductive adversarial reactions.

One of the major problems in mediation and negotiation is getting all the important players in a given case to sit down and talk about the issues in a meaningful way. The party with the "upper hand" may try to make the negotiations particularly difficult for opposing parties. Increasingly, however, all parties in environmental issues are recognizing that it is advantageous to work together toward a solution that is satisfactory for everyone. This is basically a collaborative process that seeks solutions that favor the environment while allowing activities and projects to go forward.

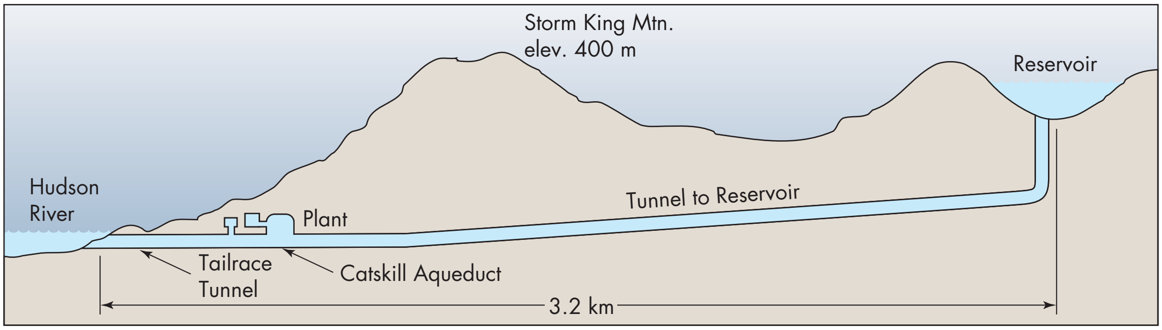
It is important to recognize that collaboration is different from and broader than compromise, which often requires giving something up to get something else. Collaboration is more comprehensive in that it asks—in fact, necessitates—that the parties work together to create opportunities for mutual gain. Collaboration creates a climate of joint problem solving. For negotiation and mediation to work, all parties must clearly and honestly state their positions and then work to see where common ground might be found. Relationships built upon mutual trust are then developed. It should come as no surprise that almost all issues are negotiable, and alternatives can often be worked out that avoid, or at least minimize, costly litigation and lengthy delays.

The Storm King Mountain Case

The Storm King Mountain dispute is a classic example of conflict between a utility company and conservationists. In 1962, the Consolidated Edison Company of New York announced plans for a hydroelectric project approximately 64 km (40 mi) north of New York City, on Storm King Mountain, part of the Hudson River Highlands, an area in the Appalachian Mountains considered by many to have unique aesthetic value. It is the only place in the eastern United States where a major river has eroded through mountains at sea level, giving the effect of a fjord.[62]

Early plans called for construction of an aboveground powerhouse, which would have required a deep cut into Storm King Mountain. The project was redesigned to site the powerhouse entirely underground, eliminating the cut on the mountain (**Figure 19.19**). However, conservationists continued

(a)



(b)

FIGURE 19.19 Hudson River Highlands (a) Storm King Mountain and the Hudson River Highlands, New York. *(Joe Deutsch)* (b) Diagram showing how the entire Storm King Mountain hydroelectric project might be placed underground. *(After Carter, L. J. 1974.* Science *184:1353–1358. Copyright 1974, American Association for the Advancement of Science)*

to oppose the project, and the issues broadened to include possible damage to fisheries. Conservationists argued that the high rate of water intake from the river would draw many fish larvae into the plant, where they would be destroyed by turbulence and abrasion. The most valuable sport fish in the river is the striped bass, and one study showed that 25 to 75 percent of the annual bass hatch might be destroyed if the plant were to operate. The fish return from the ocean to tidal water to spawn, and, since the Hudson River is the only estuary north of Chesapeake Bay where the striped bass spawn, the concern for the safety of the fisheries was justified. The problem was even more severe because the proposed plant was to be located near the striped bass spawning area.[62]

The Storm King Mountain controversy is interesting because it emphasizes the difficulty of making decisions about multidimensional issues. A utility company was trying to survive in New York City, where high peak-power demands are accompanied by high labor and maintenance costs. At the same time, conservationists were fighting to preserve a beautiful landscape and fishery resources. Both had legitimate arguments, but, in light of their special interests, it was difficult to resolve the conflicts. Existing laws and procedures were sufficient to resolve the issues, but trade-offs were necessary. Ultimately, an economic and environmental price must be paid for any decision—a price that reflects our desired lifestyle and standard of living.

The first lawsuit in the Storm King dispute was filed in 1965, and, after 16 years of intense courtroom battles, the dispute was settled in 1981. The total paper trail exceeded 20,000 pages, and, in the end, the various parties used an outside mediator to help settle their differences. This famous case has been cited as a major victory for environmentalists. Could the outcome have been decided much earlier if the various litigants had been able to sit down and talk openly about the issues? Perhaps, through the processes of negotiation and mediation, the dispute might have been settled much sooner at a lesser cost to the individual parties and society in general.[63] This case illustrates that environmental law issues may best be approached from a problem-solving viewpoint rather than an adversarial one.

Geology, the Environment, and the Future

This book started with the introduction of some philosophy and fundamental concepts associated with geology and the environment. A main message of this book is that Earth is a dynamic place and that people should not build on floodplains; of course, this is an oversimplification. There are many important linkages between geologic processes, the environment, and society, and we must pay close attention to these linkages if we are to achieve sustainability.

Avoiding an Environmental Crisis: Focusing on What Can Be Done

The concept of an environmental crisis was introduced in Chapter 1. We now turn to what can be done to eliminate development of a potential crisis that could damage human society as we know it. First, we will suggest short-term actions to avoid a potential food shortage in the next few years to decades. Second, we will discuss how we might achieve the long-term concept of sustainability over centuries of human use of Earth.

Lester Brown, a leader in understanding global environmental problems and solutions, argues that we should do three things (all are linked to food supply) to stop a human environmental crisis from developing that could cause tremendous social unrest and disturbance not previously seen:[64]

1. Control human population growth to the United Nations's "low" scenario of 7 to 8 billion people on Earth by 2050; we are presently on a path to the "middle" scenario of 8 to 9 billion people. Some keys to achieving this population growth reduction are the education of women, improved health care for children, and a general rise in the standard of living (see Chapter 1).
2. Conserve and sustain water resources, especially groundwater. Use of groundwater has allowed grain production to triple in the past half century, while the population has more than doubled. Water resources are simultaneously being depleted in all grain belts of the world (the United States, China, India, and Canada). We know how to conserve and sustain water (see Chapter 13) but need policies that include pricing water at its real value, not a subsidized lower price. We need to implement water conservation technology for agriculture and other uses sooner rather than later.
3. Control carbon emissions and minimize global warming. Each incremental increase in warming results in the loss of a small portion of our grain crops to droughts and other water-related hazards. Warming above a threshold temperature causes reduction of grain productivity. Solutions to minimize global warming were discussed in Chapter 18. They include a shift to a different mix of energy sources (especially renewable sources, such as wind and solar power) that release much less carbon dioxide and using many more energy conservation technologies, such as efficient appliances, bulbs for lighting, and more fuel-efficient automobiles. We need to transition from fossil fuels, which are contributing to global warming, to fuels produced from renewable energy, such as wind and solar power. We need to do this sooner rather than later.

Attaining Sustainability for the Future

Understanding sustainability is a main objective of this book. However, the concept of sustainability is a controversial topic. To promote sustainability, as applied to development or planning, we

must first ensure that our renewable resources, such as water, air, soil, and living things, are maintained for future generations and ecosystems. Second, we must ensure that human processes do not degrade these resources.

Sustainable use of nonrenewable resources, such as fossil fuels and minerals that are a part of our natural heritage from the geologic past, is not possible. The best we can do is to use the nonrenewable resources in ways that will allow future generations to have their fair share. Through conservation and recycling, we can greatly extend the availability of mineral resources. With respect to renewable resources, the concept of sustainability is central to future environmental planning and our preservation of a quality environment.

The important question is How can we develop a sustainable future? In discussing this topic, I make a number of value judgments about our present development as a society. These are my opinions; your opinions may be different. This discussion is not science, based upon facts and testing hypotheses, but follows from what we learn from science. This distinction is important. Our present path of overpopulation, resource consumption, and pollution is clearly not a sustainable one. What is required is development of a new path that will transform our present way of running society, with creation of wealth as a main goal, into one that integrates social, industrial, agricultural, and environmental interest into a harmonious, sustainable system.[65] This will include:[66]

- An evolution of values and lifestyles that move toward sustainability. In the United States, we are already there with respect to values. Survey after survey has confirmed that the vast majority of people in the United States state that protecting the environment should be a top priority. About half the people believe that environmental protection does not need to conflict with economic growth.
- Recognition that sustainable development needs to include all people on Earth, rich and poor alike, and that we need to provide a higher standard of living for all, without compromising the environment. That is, we should assist the disadvantaged people of the world, not take advantage of them. Working people need a living wage with which they can support their families. Exploitation of other countries' resources and labor to reduce costs of manufacturing goods or growing food undermines us all.
- Planning for future population changes, resource use, and natural hazards in a proactive way, rather than waiting for surprises or shocks and then reacting.

The world population is going to continue to increase dramatically for at least the next few decades, and this increase will be most apparent in the developing world, where birth rates are the highest. As more land is needed to house our growing population, more and more people will be put at risk in terms of their proximity to hazardous processes, such as hurricanes, flooding, landslides, volcanic activity, and earthquakes. Past experience suggests that we are not particularly well prepared to deal with many of these hazards when they occur in populated areas. Therefore, a major goal of environmental geology is to identify hazardous processes and work to minimize their potential effects through sound land-use planning, a better general understanding of the processes, and a potential range of strategies that might help us learn to better live with our planet. Achieving this goal is particularly important for the future because, as population increases, there will be continued demand for more and more land on which people can live. Urban areas will increase in size to become giant urban corridors, particularly along some of the coastal areas, where people tend to be most concentrated. Therefore, it behooves us to learn from our past mistakes and to ensure that future development is wise development.

I hope I am "preaching to the choir" and that many of you who have studied environmental geology will have a better awareness of the world around you and the geologic processes that operate within it. As a result, you are empowered to become more in tune with the natural processes of Earth and now have the knowledge to make wiser choices concerning how we use Earth resources, where we live, and how we build a society with the objective of sustainable planning. These choices are really the heart of ensuring that our future world will be safer for people and that society will live more in harmony with the environment than in the past. This is your charge as the next generation.

Making The Connection

Linking the Opening Case History About Radon Gas to the Fundamental Concepts

Consider and discuss the following questions:

1. What are the impacts of population increase on the potential radon hazard in homes?
2. Is management of the radon gas hazard possible? How is management linked to education?
3. What are some science and value issues related to the radon gas hazard?

Summary

The death rate and incidence of specific diseases vary from one area to another; some of the variability has geologic linkages. The causes are often quite complex, and a particular disease seldom has a one-cause/one-effect relationship. Nevertheless, considerable evidence suggests that the geochemical environment is a significant factor in the incidence of some serious, chronic health problems, including heart disease and cancer.

The atmosphere is a fast-flowing medium, too often used by people for waste disposal. Every year, several hundred million metric tons of pollutants enter the atmosphere above the United States from processes related to human activity. Considering the enormous volume of the atmosphere, this is a relatively small amount of material. If it were distributed uniformly, there would be fewer problems with air pollution. Unfortunately, in general, pollutants are not evenly distributed but are concentrated in urban areas or in other areas where the air naturally lingers.

Particulate-matter pollutants are small particles of solid or liquid substances that are designated PM 10 or PM 2.5, depending on size. PM 10 particles are less than 10 μm in diameter; they are released into the atmosphere by many natural processes and human activities. Desertification, volcanic eruptions, fires, and modern farming all add large amounts of particulate matter to the air. Nearly all industrial processes release particulates into the atmosphere, as does the burning of fossil fuels. Much particulate matter is easily visible as smoke, soot, or dust, but some particulate matter is not readily apparent. Particulates include airborne asbestos particles and small particles of heavy metals, such as arsenic, copper, lead, and zinc, which are usually emitted from industrial facilities, such as smelters.

Meteorological and topographic conditions in a particular urban area greatly affect the potential for air pollution problems. In particular, restricted lower-atmosphere circulation, associated with temperature inversion layers, may lead to pollution events, especially in cities lying in a "bowl" surrounded by mountains. Air pollution over an urban area is directly proportional to the emission rate of pollution and the downwind travel distance of pollutants over the city; pollution is inversely proportional to the wind velocity and the height of the mixing layer of the atmosphere over the urban area.

A growing problem in urban areas is indoor air pollution, caused by tight insulation of modern buildings, emission of toxic gases from building materials, and circulation of toxic gases, smoke, and disease-causing organisms through ventilation systems. Radon gas is a serious indoor air pollutant with a natural source.

Industrialization and urbanization have produced enormous amounts of waste and greatly compounded the problem of waste management. Around many large cities, space for new landfills is becoming hard to find, and few people wish to live near any waste disposal operation. We are headed toward a disposal crisis if the new methods and ideas of integrated waste management are not acted on soon.

Since the Industrial Revolution, waste management practices have moved from "dilute and disperse," to "concentrate and contain," to integrated waste management (IWM), which includes alternatives such as reducing, reusing, recycling, landfilling, incinerating, and composting. The goal of many of these alternatives, which can be summarized as "reduce, reuse, and recycle," is to reduce the total amount of waste that needs to be disposed of in landfills or incinerators.

The most common sites for disposal of urban waste in the United States today are sanitary landfills, in which the waste deposited each day is covered with a layer of compacted soil. Potential hazards from sanitary landfills are pollution of groundwater

by leachate (i.e., polluted water) from the site and uncontrolled production of methane. However, if methane is contained, it is a useful by-product of landfill operations. Under arid conditions, buried waste produces little leachate; in humid regions, the most suitable sites for landfills are where waste can be buried well above the water table in clay and silt soil of low hydraulic conductivity. Modern sanitary landfills have multiple barriers to prevent leachate from infiltrating the vadose zone (above the water table). Sanitary landfills have systems to monitor the vadose zone and wells to monitor groundwater. The siting and operation of sanitary landfills is regulated by federal laws.

Hazardous waste management is a serious environmental problem in the United States. Hundreds or thousands of uncontrolled disposal sites may be time bombs that could eventually cause serious public health problems. Because we continue to produce hazardous waste, it is imperative that safe disposal methods be developed and used. Land-disposal options for the management of waste include secure landfills, in which the waste is confined and the leachate is controlled; land application, in which suitable biodegradable materials are spread on the surface; deep-well injection; and incineration, with disposal of the residue by secure landfill.

The probable effects of human use of the land are called the environmental impact. The National Environmental Policy Act (NEPA) requires preparation of an environmental impact statement (EIS) for every major federal action that could significantly affect the quality of the human environment. Scoping and mitigation are important processes in environmental impact work.

Land use is an important environmental issue. Urbanization of rural areas may destroy agricultural land or damage ecosystems with high scenic or recreational value. The limited land available for urban area expansion has led to the concept of sequential and multiple land use rather than permanent consignment of land to a single use. Land use planning is essential for sound economic development and maintaining a high quality of life. The basic philosophy of sustainable planning, from an Earth science perspective, is to plan to avoid hazards, conserve natural resources, and, generally, protect the environment through the use of sound ecological principles.

Environmental law is now an important part of law. There is a move toward problem solving and mediation rather than confrontation and adversarial positions in environmental matters. When negotiation replaces inflexibility, progress in solving problems is enhanced.

Geology has an important message for our future and the environment: We live on a dynamic planet and must make careful decisions concerning where we choose to live and how we plan for sustainability. This is the essence of the linkages between geology, society, and the future. It is becoming clear that we cannot continue “business as usual” with respect to how we have treated the environment. To avoid a crisis, we need to control human population growth, conserve our water resources, and minimize human-induced global warming.

Revisiting Fundamental Concepts

Human Population Growth
Human population increase is an important factor in nearly all relationships between geology and society. Increasing numbers of people require the use of more resources and produce more chemicals and waste. Finding socially acceptable ways of controlling human population is a fundamental goal of environmental science and its subdiscipline environmental geology.

Sustainability Sustainability is part of the solution to many environmental problems, and sustaining renewable resources is an important environmental goal. How we might achieve sustainability is not entirely clear. It will require a new way of thinking that will transform our society with industrial, agricultural, and environmental interests to a system more in harmony with natural and human-modified ecosystems.

Earth as a System Understanding relationships between society and geology requires an understanding of how physical, hydrologic, and biological systems function and change and of how they are linked to the cultures and societies of the world. Linkages between systems are related to patterns of disease and pollution that kill millions of people each year, mostly in countries where access to clean water and good sanitation is not adequate.

Hazardous Earth Processes, Risk Assessment, and Perception Environmental analysis, regulations, and laws have the objective of reducing hazards and environmental degradation resulting from human interactions with the environment in activities such as waste management and use of land and other resources. Environmental impact analysis and assessment is an important part of perceiving and anticipating risks and changes that may result from a particular action, such as constructing a dam and reservoir or disposing of toxic waste.

Scientific Knowledge and Values Scientific understanding of geologic processes is a mature field of study. Applying this knowledge to environmental problems is an effort supported by our values. People desire a healthy environment and are willing to support legislation to protect and improve the quality of the air we breathe, the water we drink, and the land we live on. We also value other living things and ecosystems, and there are laws to protect ecosystems and endangered species.

Key Terms

air toxin (p. 673)
atmospheric inversion (p. 677)
environmental impact statement (EIS) (p. 693)
environmental law (p. 696)
hazardous waste (p. 687)
industrial ecology (p. 682)
integrated waste management (IWM) (p. 681)
land use planning (p. 694)
materials management (p. 681)
mitigation (p. 694)
photochemical smog (p. 678)
primary pollutant (p. 673)
radon (p. 669)
reduce, reuse, and recycle (p. 681)
sanitary landfill (p. 683)
scoping (p. 693)
secondary pollutant (p. 673)
secure landfill (p. 690)
site selection (p. 693)
sulfurous smog (p. 678)
toxicology (p. 665)

Review Questions

1. How can you define disease from an environmental viewpoint?
2. What are some possible explanations for the relationship between the geochemical environment and the incidence of heart disease?
3. What is radon, and why do we think exposure to radon gas in homes is dangerous?
4. What are the major pathways whereby radon gas may enter homes, and how may concentrations of radon gas in homes be reduced?
5. What are the major air pollutants?
6. What are the processes that concentrate air pollutants in the urban environment?
7. What is materials management?
8. What are the three *R*s?
9. Define *sanitary landfill*.
10. What is leachate?
11. How are sanitary landfills monitored?
12. What is a secure landfill?
13. Why is Love Canal important?
14. What are the common methods of hazardous waste management?
15. What are the major components of an environmental impact statement?
16. What is scoping?
17. What is a negative declaration?
18. What are the major steps in land use planning?
19. How do negotiation and mediation enter into the practice of environmental law?

Critical Thinking Questions

1. Consider the inverse relationship between water hardness and incidence of heart disease presented in this chapter. Three hypotheses detailing the relationship were stated, including the observation that hardness of water has nothing to do with heart disease. Develop a strategy for testing each hypothesis.
2. Your college or university is trying to find a 10-acre site on or adjacent to the campus for future development of an academic center. Complete a survey of your campus and surrounding area and make a recommendation concerning where the new buildings should go. What criteria did you use in your decision-making process? What values are involved in your decision?

3. Is the concept of sustainability a valid one that you would support? What do you think is necessary to sustain our renewable resources?

4. Do you believe the three steps stated by Lester Brown are necessary to avoid an environmental crisis in the near future? Why? Why not?

5. Discuss how we might eventually develop a sustainable future. Hint: Consider the section "Attaining Sustainability for the Future."

6. Complete an audit of your personal waste production and disposal where you live. How much are you presently recycling, and how much do you estimate (at the high end) that you can recycle? If everyone in your neighborhood did this, what would be the impact on the local waste situation?

7. For the region in which you live, identify potential hazardous wastes that are produced by homes, businesses, and industry or agriculture. How are these wastes currently being treated, and what could be done to develop a better management strategy if there were problems?

8. Where does the e-waste from your university or college go? What about your community e-waste? Was it difficult to find these answers?

Companion Website

www.mygeoscienceplace.com

PEARSON mygeoscience™ place

Introduction to Environmental Geology, 5e premium website contains numerous multimedia resources accompanied by assessments to aid in your study of the topics in this chapter. The use of this site's learning tools will help improve your understanding of environmental geology. Utilizing the access code that accompanies this text, visit **www.mygeoscienceplace.com** in order to:

- **Review** key chapter concepts.
- **Read** with links to the Pearson eText and to chapter-specific web resources.
- **Visualize and Explore** the most challenging chapter topics using the Geoscience Animation Library and *Hazard City, Assignments in Applied Geology*.
- **Test** yourself with online quizzes.

Appendix A

Minerals

Characteristic Properties of Minerals

Characteristic properties of specific minerals often have aesthetic or utility value to people. For example, Stone Age people valued natural volcanic obsidian glass and fine-grained quartz, called flint, for making tools. High-quality stone tools were collected and traded among different tribes on a regional scale. Similarly, native copper, when discovered in the Great Lakes region by Native Americans, was valued for its metallic properties of luster and malleability (discussed later) and was used for jewelry and tools. Many ancient cultures, in addition to our own, have valued gemstones such as rubies and sapphires for their beauty. Historically, one of the most valued minerals has been halite (NaCl), or common table salt, because all animals, including people, need it to live. Halite has been mined and obtained from evaporation ponds for thousands of years. Some clay minerals have been highly valued because they can be molded into useful containers, pots, and decorative statues and painted with black, red, and orange paints made from still other minerals. Today, specific physical properties of a wide variety of minerals are used for everything from ceramics to electronics, metallurgy, agriculture, and personal jewelry. Now let us take a closer look at properties of minerals.

Identifying Minerals

As discussed in Chapter 3, the identification of minerals from hand specimens is a combination of pattern recognition and testing for particular properties or characteristics of minerals. These include color, specific gravity, cleavage, crystal form, fracture, hardness, luster, and other diagnostic properties characteristic of a particular mineral or group of minerals.

Color

The *color* of a mineral can be misleading because a given mineral may have several different colors, or several different minerals may have the same color. Depending on the impurities present, quartz may be clear, pink, purple, yellow, or smoky black. The color a mineral leaves as a powder when rubbed on a porcelain plate, or "streak plate," is more reliable. The mineral hematite, Fe_2O_3, may be dull black or a shiny, dark metallic silver color, but its streak is always red.

Specific Gravity

The *specific gravity* of a mineral is the density of a mineral compared with the density of water. Water has a specific gravity of 1. The specific gravity of minerals varies from about 2.2 for halite to 19.3 for gold. Most minerals have specific gravities of about 2.5 to 4.5. In practice, we take a sample of a mineral in hand, heft it, and estimate if it is light, medium, or heavy.

Cleavage

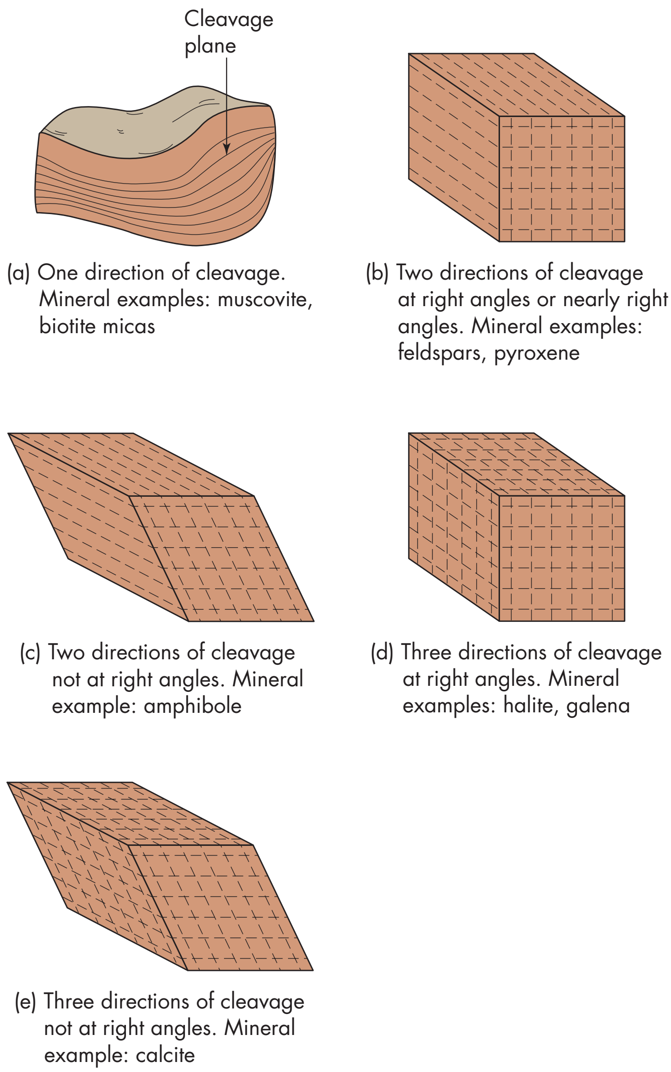
Cleavage is the way a mineral tends to part along planes of weakness determined by the internal crystalline structure and types of chemical bonds in the mineral. Several common types of cleavage are shown in **Figure A.1**.

Crystal Form

Crystal form is also a useful diagnostic property for mineral identification (see Figure 3.5). For example, the elongated hexagonal pointed crystals of quartz (SiO_2), regardless of the color of the specimen, are diagnostic, as are the cube-shaped crystals of pyrite (FeS_2).

Fracture

The way a mineral commonly breaks, or *fractures*, may also help identify it. Terms to describe fracture include blocky, splintery, fibrous, or conchoidal. Conchoidal means that the material fractures like glass, usually with curved surfaces that look something like a clamshell.



(a) One direction of cleavage. Mineral examples: muscovite, biotite micas

(b) Two directions of cleavage at right angles or nearly right angles. Mineral examples: feldspars, pyroxene

(c) Two directions of cleavage not at right angles. Mineral example: amphibole

(d) Three directions of cleavage at right angles. Mineral examples: halite, galena

(e) Three directions of cleavage not at right angles. Mineral example: calcite

FIGURE A.1 Some common types of cleavage with mineral examples Cleavage, with the exception of mica, is shown by dashed lines. (a) Mica has one cleavage direction and breaks into sheets. (b) Feldspar and pyroxene have two cleavage directions and break at right or nearly right angles. (c) Amphibole has two directions of cleavage that do not meet at right angles. (d) Halite and galena have three cleavage directions that meet at right angles. They break into cube-shaped fragments. (e) Calcite also has three cleavage directions, but they do not meet at right angles. Calcite breaks into rhombohedrons.

Hardness

The relative *hardness* of minerals is determined by using a scale suggested by the Austrian mineralogist Friedrich Mohs. The scale ranges from 1 to 10, where 1, the hardness of the mineral talc, is the softest, and 10, the hardness of diamond, is the hardest (**Table A.1**). Unit increase in the scale is not equivalent to an equal increase in hardness. The hardness of a mineral is determined by a series of tests using the Mohs Hardness scale. Any mineral or substance will scratch a mineral with a lower hardness on the Mohs scale. Trying to scratch a mineral sample of unknown hardness with a knife blade (hardness about 5.5) will tell you if your unknown mineral is harder or softer than 5.5. Then, using other minerals or substances on the Mohs scale, you can determine the relative hardness of the unknown mineral sample.

Luster

Luster refers to the way light is reflected from a mineral. Some minerals have metallic luster with high reflectivity. Other minerals are translucent or transparent to light and have a nonmetallic luster. Some minerals have more than one luster. For example, some samples of graphite have metallic luster and others are nonmetallic. Terms to describe luster include pearly, greasy, and earthy.

Table A.2 (page A-5) contains a list of some of the common minerals and their properties. An identification key (**Table A.3**, page A-10) may assist in the actual identification. In Table A.3 the first step is to decide if the mineral has a metallic or a nonmetallic luster. The second step is to determine the relative hardness. Third, decide whether the mineral has a cleavage. Fourth, use characteristic properties, including streak and fracture, to assist in the final identification.

It is important to note that actual identification of minerals in the field or in the laboratory from small specimens, using simple tests and perhaps a hand lens to determine cleavage and other properties, is basically a pattern recognition exercise. After you have looked at a number of minerals over a period of time and have learned how particular minerals vary, you will become more proficient at identifying a particular sample. When positive identification is necessary, mineralogists will use a variety of sophisticated equipment to determine the chemical composition and internal structure to positively identify minerals.

TABLE A.1 Mohs Hardness Scale

	Relative Hardness	Mineral	Comment	Hardness of Common Hardness Materials
Softest	1	Talc	Softest mineral known; used to make powder	Graphite, "lead" in pencils (1–2)
	2	Gypsum	Used to make wall board	Fingernail (2.5)
	3	Calcite	Main mineral in marble, rock	Copper penny (3.0)
	4	Fluorite	Mined for fluorine, used in glass and enamel	
	5	Apatite	Enamel of your teeth	Steel knife blade, Glass (5.5–6)
	6	Orthoclase	Common rock-forming mineral	
	7	Quartz	When purple is gemstone amethyst; birthstone for February	Hard steel file (6.5)
	8	Topaz	When transparent is gemstone; birthstone for November	
Hardest	9	Corundum	When red is ruby, gemstone; birthstone for July; when blue is sapphire, gemstone; birthstone for September	
	10	Diamond	Hardest known mineral; gemstones are extremely brilliant	

Note: The scale is relative, and unit increases in hardness do not represent equal increases in hardness.

TABLE A.2 Properties and Environmental Significance of Selected Common Minerals

Mineral Group	Mineral	Chemical Formula	Color	Hardness	Other Characteristics	Comment
Silicates	Plagioclase feldspars	$(Na,Ca)Al(Si,Al)Si_2O_8$	Usually white or gray, but may be others	6	Two good cleavages at approximately 90° and may have fine striations on one of the cleavage surfaces	One of the most common of the rock-forming minerals; is a group of feldspars ranging from sodium- to calcium-rich; important industrial minerals
	Alkali feldspars	$(Na,K)AlSi_3O_8$	Gray, white to pink	6	Two good cleavages at 90°; may be translucent to opaque with vitreous luster; white streak	One of the most common of the rock-forming minerals; the potassium-rich alkali feldspar orthoclase is widely used in the porcelain industry and in a variety of industrial processes
	Quartz	SiO_2	Varies from colorless to white, gray, pink, purple, and several others, depending on impurities	7	Often has good crystal shape with six sides; conchoidal fracture	Very common rock-forming mineral; resistant to most chemical weathering; basic constituent of glasses and fluxes; commonly used as abrasive material; colored varieties such as amethyst and others provide a number of semiprecious gemstones
	Pyroxene	$(Ca,Mg,Fe)_2Si_2O_6$	Usually greenish to black	5–6	Crystals are commonly short and stout; two cleavages at about 90°	Important group of rock-forming minerals; particularly common in rocks; weathers rather quickly; an important commercial source of asbestos when they crystallize, forming a mass of easily separated thin fibers
	Amphibole	$(Na,Ca)_2(Mg,Al,Fe)_5Si_8O_{22}(OH)_2$	Generally light green to black	5–6	Distinguished from pyroxene by the cleavage angle being 120° rather than 90°; amphibole also generally has a better cleavage with higher luster than does pyroxene	Important rock-forming mineral; particularly for igneous and metamorphic rocks; relatively nonresistant to weathering

(*Continued*)

TABLE A.2 (*Continued*)

Mineral Group	Mineral	Chemical Formula	Color	Hardness	Other Characteristics	Comment
	Olivine	$(Mg,Fe)_2SiO_4$	Generally green, but also may be yellowish	6.5–7	Generally has a glassy luster, no cleavage	Important rock-forming mineral, particularly for igneous and metamorphic rocks; relatively nonresistant to chemical weathering
	Clay	Various hydrous aluminum silicates with elements such as Ca, Na, Fe, Mg	Generally white but may vary due to impurities	1–2	Generally found as soft, earthy masses composed of very fine grains; may have an earthy odor when moist; often difficult to identify the particular clay mineral from hand specimen	Clay minerals are very important from an environmental viewpoint; many uses in society today; clay-rich soils often have many engineering geology problems
	Biotite (black mica)	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	Black to dark brown	2.5–3	Breaks apart in parallel sheets as a result of excellent cleavage in one direction	Important rock-forming mineral common in igneous and metamorphic rocks
	Muscovite (white mica)	$KAl_2(AlSi_3)O_{10}(OH)_2$	Colorless to light gray or green or even brown if the specimen is several millimeters thick	2–3	Breaks apart into thin sheets due to excellent cleavage in one direction	Important rock-forming mineral, particularly for igneous and metamorphic rocks; used for several purposes, including industrial roofing materials, paint, and rubber
Carbonates	Calcite	$CaCO_3$	Colorless, but may have a variety of colors resulting from impurities	3	Effervesces strongly in dilute hydrochloric acid; often breaks apart to characteristic rhombohedral pieces as a result of two good cleavages at 78°; transparent varieties display double refraction, when a single dot on a piece of white paper looks like two dots if viewed through the mineral	Main constituent of the important sedimentary rock limestone and the metamorphic rock marble; associated with a variety of environmental problems with these rocks, including the development of sinkholes; chemically weathers rapidly; used in a variety of industrial processes including asphalts, fertilizers, insecticides, and plastics

TABLE A.2 (*Continued*)

Mineral Group	Mineral	Chemical Formula	Color	Hardness	Other Characteristics	Comment
	Dolomite	$(Ca,Mg)CO_3$	Generally white but may be a variety of other colors, including light brown and pink	3.5–4	When powdered, will slowly effervesce in dilute hydrochloric acid; two cleavages at 78°; may be transparent to translucent and have a vitreous to pearly luster	Common mineral in the important sedimentary rock type dolomite and dolomitic limestones
	Malachite	$CuCO_3 \cdot Cu(OH)_2$	Bright to emerald green, but may be dark green	3.5–4	Effervesces slightly in dilute hydrochloric acid and turns the acid solution green; often displays a swirling banded structure of light and darker green bands	Valued as a decorative stone; used in jewelry making and is a copper ore
Oxides	Hematite	Fe_2O_3	Usually various shades of reddish brown to red to dark gray	5.5–6.5	Streak is dark red	A common mineral found in small amounts in many igneous rocks, particularly basaltic rocks
	Magnetite	Fe_3O_4	Black	6	Magnetic	The most important ore of iron
	Bauxite	Hydrous aluminum oxides	Variable from yellow to brown, gray, and white	1–3	Usually has an earthy luster composed of dull, earthy masses with a colorless streak	Primary ore of aluminum; results from intense weathering of rocks in tropical and subtropical environments
	Limonite	Hydrous iron oxide with small amounts of other elements	Generally yellow to yellow-brown or black	1–5.5	Often present as earthy masses or in the form of a crust	Limonite is a term often used to describe a variety of very fine-grained hydrous oxides. Often forms from the chemical weathering of iron minerals and is present as "rust"

(*Continued*)

TABLE A.2 (*Continued*)

Mineral Group	Mineral	Chemical Formula	Color	Hardness	Other Characteristics	Comment
Sulfides	Pyrite	FeS_2	Generally a brassy yellow tarnishing to brown	6–6.5	Often present as well-formed cubic crystals with striations on crystal faces	Has been used in the production of sulfuric acid, but mostly known for adding sulfur content to coal and contributing to the formation of acid-rich waters that result from the weathering of the mineral
	Chalcopyrite	$CuFeS_2$	Dark to brassy yellow, tarnishing to iridescent films that are reddish to blue-purple	3.5–4	Easily disintegrates; greenish black streaks; lacks cleavage	An important ore of copper; often associated with gold and silver ores
	Galena	PbS	Silver gray	2.5	Gray to black streak; high specific gravity; general metallic luster	Primary ore of lead
Sulfates	Gypsum	$CaSO_4 \cdot 2H_2O$	Generally colorless to white, but may have a variety of colors due to impurities	2	Often is transparent to opaque with one perfect cleavage; may form fibrous crystals but often is an earthy mass	Several industrial uses in making of plaster of Paris for construction material, fertilizer, and flux for pottery
	Anhydrite	$CaSO_4$	Commonly white but may be colorless	3–3.5	Commonly observed as massive fine aggregates; may be translucent to transparent; colorless streak	Used for the production of sulfuric acid, as a filler material in paper, and occasionally as an ornamental stone
Halides	Fluorite	CaF_2	Variable colors, often purple, yellow, white, or green	4	Often observed as cubic crystals but may also be massive; four perfect cleavages	A number of industrial uses, including a flux in the metal industry, certain lenses, and in the production of hydrofluoric acid

TABLE A.2 (*Continued*)

Mineral Group	Mineral	Chemical Formula	Color	Hardness	Other Characteristics	Comment
	Halite	$NaCl$	Generally colorless to white, but may be a variety of colors due to impurities	2–2.5	Salty taste; often forms a cubic form due to three perfect cleavages	Common table salt; application to snowy roads in winter may pollute water; suggested as a host rock for nuclear waste
Native Elements	Gold	Au	Gold yellow	2.5–3	Crystals are rare; extremely high specific gravity; very ductile and malleable	Primary use as a monetary standard; used in jewelry and in the manufacture of computer chips and other electronics
	Diamond	C	Generally colorless but also occurs in various shades of yellow and blue	10	Commonly cut to display brilliant luster	Used in industrial abrasives and, of course, jewelry
	Graphite	C	Black to gray	1–2	Often occurs as foliated masses; black streak and marks paper as well; is the "lead" in pencils	A variety of industrial uses including lubricants, dyes, and the "lead" in pencils
	Sulfur	S	Usually yellow when pure but may be brown to black from impurities	1.5–2.5	Characteristic sulfurous smell	Often a by-product of the oil industry; may be used to manufacture sulfuric acid

Note: The scale is relative, and unit increases in hardness do not represent equal increases in hardness.

Source: Modified after Davidson, J. P., Reed, W. E., and Davis, P. M. 1997. *Exploring Earth.* Upper Saddle River, NJ: Prentice Hall; and Birchfield, B. C., Foster, R. J., Keller, E. A., Melhom, W. N., Brookins, D. G., Mintt, L. W., and Thurman, H. V. 1982. *Physical geology.* Columbus, OH: Charles E. Merrill.

TABLE A.3 Key to Assist Mineral Identification.

To use this table, (1) make a decision as to whether the luster of the mineral to be identified is nonmetallic or metallic. If it is nonmetallic, decide whether it is a light-colored or a dark-colored mineral; (2) use a knife blade to determine if the mineral specimen is harder or softer than the knife blade; (3) look for evidence of cleavage; and (4) compare your samples with the other properties shown here and use Table A.2 for final identification.

Light-colored nonmetallic luster	Hard—not scratched by knife	Shows cleavage	White or flesh colored; 2 cleavage planes at nearly right angles; hardness, 6. Large crystals that show irregular veining are perthite.	Orthoclase (potassium feldspar)
			White or green-gray; 2 cleavage planes at nearly right angles; hardness, 6; striations on cleavage.	Plagioclase
		No cleavage	White, clear, or any color; glassy luster; transparent to translucent; hexagonal (six-sided) crystals; hardness, 7; conchoidal fracture.	Quartz
			Various shades of green and yellow; glassy luster; granular masses and crystals in rocks; hardness, 6.5–7 (apparent hardness may be much less).	Olivine
	Soft—scratched by knife	Shows cleavage	Colorless to white; salty taste; 3 perfect cleavages forming cubic fragments; hardness, 2–2.5.	Halite
			White, yellow to colorless; 3 perfect cleavages forming rhombohedral fragments; hardness, 3; effervesces with dilute hydrochloric acid.	Calcite
			Pink, colorless, white, or dark; rhombohedral cleavage; hardness, 3.5–4; effervesces with dilute hydrochloric acid only if powdered.	Dolomite
			White to transparent; 1 perfect cleavage; hardness, 2.	Gypsum
			Green to white; feels soapy; 1 cleavage; hardness, 1.	Talc
			Colorless to light yellow or green; transparent in thin sheets that are very elastic; 1 perfect cleavage; hardness, 2–3 (white mica).	Muscovite
			Green to white; fibrous cleavage; may form veins.	Asbestos
		No cleavage	Green to white; feels soapy; hardness, 1.	Talc
			White to transparent; hardness, 2.	Gypsum
			Yellow to greenish; resinous luster; hardness, 1.5–2.5.	Sulfur

TABLE A.3 (*Continued*)

Dark-colored nonmetallic luster	Hard—not scratched by knife	Shows cleavage	Black to dark green; 2 cleavage planes at nearly 90°; hardness, 5–6.	Pyroxine
Dark-colored nonmetallic luster	Hard—not scratched by knife	Shows cleavage	Black to dark green; 2 cleavage planes about 120°; hardness, 5–6.	Amphibole
Dark-colored nonmetallic luster	Hard—not scratched by knife	No cleavage	Various shades of green and yellow; glassy luster; granular masses and crystals in rocks; hardness, 6.5–7 (apparent hardness may be much less).	Olivine
Dark-colored nonmetallic luster	Hard—not scratched by knife	No cleavage	White, clear, or any color; glassy luster; transparent to translucent; hexagonal (six-sided) cyrstals; hardness, 7; conchoidal fracture.	Quartz
Dark-colored nonmetallic luster	Hard—not scratched by knife	No cleavage	Red to brown; red streak; earthly appearance; hardness, 5.5–6.5 (apparent hardness may be much less).	Hematite
Dark-colored nonmetallic luster	Soft—scratched by knife	Shows cleavage	Brown to black; cleavage, 1 direction; hardness, 2.5–3 (black mica).	Biotite
Dark-colored nonmetallic luster	Soft—scratched by knife	Shows cleavage	Various shades of green; cleavage, 1 directon; hardness, 2–2.5 (green "mica").	Chlorite
Dark-colored nonmetallic luster	Soft—scratched by knife	No cleavage	Red to brown; red streak; earthy appearance; hardness, 5.5–6.5 (apparent hardness may be less).	Hematite
Dark-colored nonmetallic luster	Soft—scratched by knife	No cleavage	Lead-pencil black; smudges fingers; hardness, 1–2; 1 cleavage that is apparent only in large crystals.	Graphite
Dark-colored nonmetallic luster	Soft—scratched by knife	No cleavage	Yellow-brown to dark brown; may be almost black; streak yellow-brown; earthy; hardness, 1–5.5 (usually soft).	Limonite
Metallic luster			Black; strongly magnetic; hardness, 6.	Magnetite
Metallic luster			Lead-pencil black; smudges fingers; hardness, 1–2; 1 cleavage that is apparent only in large crystals.	Graphite
Metallic luster			Brass yellow; black streak; cubic crystals, commonly with striations; hardness, 6–6.5.	Pyrite
Metallic luster			Brass yellow; may be tarnished; black streak; hardness, 3.5–4; massive.	Chalcopyrite
Metallic luster			Shiny gray; black streak; very heavy; cubic cleavage; hardness, 2.5.	Galena

Source: Modified after Birchfield, B. C., Foster, R. J., Keller, E. A. Melhom, W. N., Brookins, D. G., Mintt, L. W., and Thurman, H. V. 1982. *Physical geology*. Columbus, OH: Charles E. Merrill.

Appendix B

Rocks

In Chapter 3 we stated that a rock is an aggregate of one or more minerals. In traditional geologic investigations, this is the most commonly used definition. The terminology of environmental geology is somewhat different; in environmental geology, we are primarily concerned with properties that affect engineering design and environmental problems. In environmental and engineering geology, the term *rock* is reserved for Earth materials that cannot be removed without blasting using explosives such as dynamite; Earth materials that can be excavated with normal earth-moving equipment, for example, a shovel or a bulldozer, are called soil. Thus, a very friable, or loosely compacted, poorly cemented sandstone may be considered a soil, whereas a well-compacted clay may be called a rock. This pragmatic terminology conveys more useful information to planners and designers than do the conventional terms. Clay, for example, is generally unconsolidated and easily removed. A contractor, assuming that a material described as clay is a soil, might bid low for an excavation job, thinking that the material can be removed without blasting. If the clay turns out to be well compacted, however, it may have to be blasted, which is a much more expensive process. Performing a preliminary investigation and forewarning the contractor to consider the clay a rock can avoid this kind of error. (Soils and their properties are considered in detail in Chapter 16.)

Identifying Rocks

Rocks are composed of minerals. Whereas some rocks contain only one mineral, most contain several. As it is for minerals, the identification of rocks from a hand specimen is primarily a pattern recognition exercise. However, there are some useful hints that will assist you. The first task is to decide if the rock is igneous, sedimentary, or metamorphic. Sometimes this decision is not as easy as you might think. It is particularly difficult to identify rocks that are fine grained. A specimen is considered fine grained if you cannot see individual mineral grains with your naked eye. It is advisable to use a magnifying glass or hand lens to assist you in your evaluation of the properties of minerals and rocks. Some general rules of thumb will assist you in getting started: (1) If the sample is composed of bits and pieces of other rocks, it is most likely sedimentary; (2) if the rock specimen is foliated (a feature sometimes called rock cleavage, produced by the parallel alignment of mineral grains), then it is metamorphic; (3) if individual mineral crystals are relatively coarse grained, meaning you can see them with the naked eye or easily with a hand lens, and the crystals are interlocking and composed of minerals such as quartz and feldspar, it is probably a plutonic igneous rock such as granite; (4) if the rock is mostly fine grained but contains some larger crystals (phenocrysts), it is probably an extrusive igneous rock; (5) if the rock is relatively soft and effervesces when diluted hydrochloric acid is applied, it is probably a carbonate rock, most likely limestone or, if metamorphic, marble; (6) if it's a really grungy, soft, highly weathered, or altered rock, as many in nature seem to be, you are going to have some problems identifying it!

Strength of Common Rock Types

The strength of a rock is commonly reported in terms of its compressive strength, which is the compression, as mechanically applied in a viselike machine, necessary to break or fracture the specimen. The strength of a rock is reported as a force per unit area, which in the metric system is reported in Newtons per meter squared (N/m^2). Ranges of compressive strength for some of the common rock types are shown in **Table B.1**.

TABLE B.1 Strength of Common Rock Types

	Rock Type	Range of Compressive Strength (10^6 N/m^2)	Comments
Igneous	Granite	100 to 280	Finer-grained granites with few fractures are the strongest. Granite is generally suitable for most engineering purposes.
	Basalt	50 to greater than 280	Brecciated zones, open tubes, or fractures reduce the strength.
Metamorphic	Marble	100 to 125	Solutional openings and fractures weaken the rock.
	Gneiss	160 to 190	Generally suitable for most engineering purposes.
	Quartzite	150 to 600	Very strong rock.
Sedimentary	Shale	Less than 2 to 215	May be a very weak rock for engineering purposes; careful evaluation is necessary.
	Limestone	50 to 60	May have clay partings, solution openings, or fractures that weaken the rock.
	Sandstone	40 to 110	Strength varies with degree and type of cementing material, mineralogy, and nature and extent of fractures.

Source: Data primarily from Bolz, R. E., and Tuve, G. L., eds. 1973. *Handbook of tables for applied engineering science.* Cleveland, OH: CRC Press.

Physical Properties of Rocks

Physical properties of rocks include color, specific gravity, relative hardness, porosity, permeability, texture, and strength.

Color. The color of a rock varies depending upon the minerals present and the amount of weathering that has occurred. Rocks encountered in their natural environment are various shades of light gray to brown to black. They have black to orange linear stains frequently, at the surface, produced by iron oxides.

Specific Gravity and Relative Hardness. The same definition of specific gravity we gave for minerals applies to rocks and refers to the weight of the rock relative to the weight of water. Some rocks are lighter than water and will float. For example, pumice, a light-colored, volcanic rock with many vesicles, or cavities, is lighter than water. Rocks become heavier as iron- and magnesium-bearing minerals become more abundant. There is no scale for relative rock hardness similar to the Mohs scale for minerals. Soft rocks can be broken with your fingers, and hard rocks require a sledgehammer to break apart.

Porosity and Permeability. *Porosity* is the percentage of a rock's volume that contains empty space between grains, or open space in fractures. *Permeability* is the capacity of a porous rock to transmit a fluid, usually oil or water (see Chapter 11). The coefficient of permeability is known as hydraulic conductivity with units of velocity (length per unit time). Values of porosity and hydraulic conductivity for several types of rocks and sediments are shown in Table 3.4. The properties of porosity and permeability are very important in understanding many environmental problems and geologic hazards, including waste disposal, water pollution, landsliding, and even earthquakes.

Texture. The texture of a rock refers to the size, shape, and arrangement of the crystals or grains within it. In general, a rock is fine grained if you cannot see mineral crystals or grains with your naked eye; a rock is considered coarse grained if crystals or grains are visible. The shape of crystals and grains varies from regular and rounded to interlocking and angular. Angular grains are irregular with sharp corners. A rock may have lots of openings between grains or in fractures with a relatively high porosity. If these openings are partially filled with smaller grains or cementing materials, the porosity is

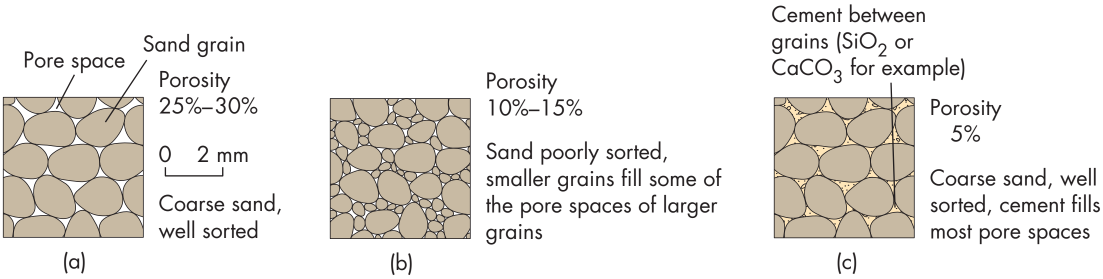


FIGURE B.1 (a) **Porosity** of a well-sorted coarse sand. (b) Poorly sorted sand. (c) Well-sorted sand with grains cemented together.

reduced. Porosity decreases from about 30 percent to 5 percent as pore spaces are filled with smaller grains or cementing material such as calcite ($CaCO_3$), quartz (SiO_2), or gypsum ($CaSO_4 \cdot 2H_2O$). Coarse grains of sand (1 to 2 mm, or 0.04 to 0.08 in., in diameter) are shown in **Figure B.1a**. If the range of sizes of grains is large, the distribution of grains is *poorly sorted* (Figure B.1b). Conversely, if the grains of sand are all approximately the same size, the distribution of grains is described as *well sorted* (Figure B.1a, c).

Other rock textures are characterized by vesicles, or cavities, formed by gas expansion during their formation. For example, vesicular rocks commonly occur near the surface of a lava flow where gas is escaping.

Appendix C

Maps and Related Topics

Topographic Maps

As the name suggests, topographic maps illustrate the topography at the surface of Earth. The topographic maps show an area's natural and human-made features graphically. Elevations and some other natural features are shown by contour lines, which are lines of equal elevation. Individual contour lines on a topographic map are a fixed interval of elevation apart, and this interval is known as the *contour interval*. Common contour intervals are 5, 10, 20, 40, 80, or 100 meters or feet. The actual contour interval of a particular map depends upon the topography being represented as well as the scale of the map. If the topography has a relatively low relief (difference in elevation between the highest point and lowest point of a map), then the contour interval may be relatively small, but if the relief is large, then larger contour intervals are necessary or the lines will become so bunched up as to be impossible to read. This brings up an important point: Where contour lines are close together, the surface of Earth at that point has a relatively steep slope, compared to other areas where the contour lines are farther apart.

The scale of a topographic map (or of any map, for that matter) may be delineated in several ways. First, a scale may be stated as a ratio, say 1 to 24,000 (1:24,000), which means that 1 inch on a map is equal to 24,000 inches or 2,000 feet on the ground. Second, a topographic map may have a bar scale often found in the lower margin of the map useful for measuring distances. Finally, scales of some maps are stated in terms of specific units of length on the map; for example, it might be stated on the map that 1 inch equals 200 feet. This means that 1 inch on the map is equivalent to 200 feet (which is 2,400 inches) on the ground. In this example we could also state that the scale is 1 to 2,400. The most common scale used by the U.S. Geological Survey Topographic Maps is 1:24,000, but scales of 1:125,000 or smaller are also used. Remember, 1 ÷ 24,000 is a larger number than 1 ÷ 125,000, so 1 ÷ 125,000 is the smaller scale. The smaller the scale of maps of similar physical map size, the more area is shown.

In addition to contour lines, topographic maps also show a number of cultural features, such as roads, houses, and other buildings. Features such as streams and rivers are often shown in blue. In fact, a whole series of symbols are commonly used on topographic maps. These symbols are shown in **Figure C.1**.

Reading Topographic Maps

Reading or interpreting topographic maps is as much an art as it is a science. After you have looked at many topographic maps that represent the variety of landforms and features found at the surface of Earth, you begin to recognize these forms by the shapes of the contours. This is a process that takes a fair amount of time and experience in looking at a variety of maps. However, there are some general rules that do help in reading topographic maps.

- Valleys containing rivers or even small streams have contours that form *V*s that point in the upstream direction. This is sometimes known as the *rule of V*s. Thus, if you are trying to draw the drainage pattern that shows all the streams, you should continue the stream in the upstream direction as long as the contours are still forming a *V* pattern. Near a drainage divide, the *V*s will no longer be noticeable.
- Where contour lines are spaced close together, the slope is relatively steep, and where contour lines are spaced relatively far apart, the slope is relatively low. Where contour lines that are spaced relatively far apart change to become closer together, we say a "break in slope" has occurred. This is commonly observed at the foot of a mountain or where valley side slopes change to a floodplain environment.
- Contours near the upper parts of hills or mountains may show a closure. These may be relatively oval or round for a conical peak or longer and narrower for a ridge. Remember, the actual

Control data and monuments

Vertical control	
Third order or better, with tablet	BM 16.3
Third order or better, recoverable mark	120.0
Bench mark at found section corner	BM 18.6
Spot elevation	5.3

Contours

Topographic
Intermediate
Index
Supplementary
Depression
Cut; fill
Bathymetric
Intermediate
Index
Primary
Index primary
Supplementary

Boundaries

National	
State or territorial	
County or equivalent	
Civil township or equivalent	
Incorporated city or equivalent	
Park, reservation, or monument	

Surface features

Levee	Levee
Sand or mud area, dunes, or shifting sand	Sand
Intricate surface area	Strip mine
Gravel beach or glacial moraine	Gravel
Tailings pond	Tailings pond

Mines and caves

Quarry or open pit mine	
Gravel, sand, clay, or borrow pit	
Mine dump	Mine dump
Tailings	Tailings

Vegetation

Woods	
Scrub	
Orchard	
Vineyard	
Mangrove	Mangrove

Glaciers and permanent snowfields

Contours and limits
Form lines

Marine shoreline

Topographic maps
Approximate mean high water
Indefinite or unsurveyed
Topographic-bathymetric maps
Mean high water
Apparent (edge of vegetation)

Coastal features

Foreshore flat	Mud
Rock or coral reef	Reef
Rock bare or awash	
Group of rocks bare or awash	
Exposed wreck	
Depth curve; sounding	3
Breakwater, pier, jetty, or wharf	
Seawall	

Rivers, lakes, and canals

Intermittent stream	
Intermittent river	
Disappearing stream	
Perennial stream	
Perennial river	
Small falls; small rapids	
Large falls; large rapids	
Masonry dam	
Dam with lock	
Dam carrying road	
Perennial lake; Intermittent lake or pond	
Dry lake	Dry lake
Narrow wash	
Wide wash	Wide wash
Canal, flume, or aquaduct with lock	
Well or spring; spring or seep	

Submerged areas and bogs

Marsh or swamp	
Submerged marsh or swamp	
Wooded marsh or swamp	
Submerged wooded marsh or swamp	
Rice field	Rice
Land subject to inundation	Max pool 431

Buildings and related features

Building
School; church
Built-up area
Racetrack
Airport
Landing strip
Well (other than water); windmill
Tanks
Covered reservoir
Gaging station
Landmark object (feature as labeled)
Campground; picnic area
Cemetery: small; large

Roads and related features

Roads on Provisional edition maps are not classified as primary, secondary, or light duty. They are all symbolized as light duty roads.

Primary highway
Secondary highway
Light duty road
Unimproved road
Trail
Dual highway
Dual highway with median strip

Railroads and related features

Standard gauge single track; station
Standard gauge multiple track
Abandoned

Transmission lines and pipelines

Power transmission line; pole; tower	
Telephone line	Telephone
Aboveground oil or gas pipeline	
Underground oil or gas pipeline	Pipeline

FIGURE C.1 Some of the common symbols used on topographic maps prepared by the U.S. Geological Survey. *(From U.S. Geological Survey)*

elevation of a peak is higher than the last contour shown and may be estimated by taking half the contour interval. That is, if the highest contour on a peak were 1,000 m with a contour interval of 50 m, then you would assume that the top of the mountain is 1,025 m.

- Topographic depressions that form closed contours have hachure marks on the contours and are useful in indicating the presence of such a depression.
- Sometimes the topography on a slope is hummocky and anomalous to the general topography of the area. Such hummocky topography is often suggestive of the existence of mass wasting processes and landslide deposits.

In summary, after observing a variety of topographic maps and working with them for some time, you will begin to see the pattern of contours as an actual landscape consisting of hills and valleys and other features.

Locating Yourself On A Map

The first time you take a topographic map into the field with you, you may have some difficulty locating where you are. Determining where you are is crucial in trying to prepare maps to show particular features—for example, the locations of floodplains, landslides, or other features. One way to locate yourself on a map is to recognize certain features such as mountain peaks, intersections of roads, a prominent bend in a road or river, or some other readily recognized feature. Then work it out from there with a compass. That is, you might take a bearing (compass direction) to several prominent features and draw these bearings on the map; your location is where they intersect. Today, however, we have more modern technology for locating ourselves and working with maps. Global Positioning Systems (GPS) are readily available at a very modest price and assist in locating a position on the surface of Earth. Hand-held GPS systems are readily available today and can generally locate your position on the ground with an accuracy of about 30 m. The GPS receivers work by receiving signals from three or four satellites and measuring the distance from the satellite to your location. This is done by measuring the time it takes for the signal from your receiver to reach the satellite and return. The accuracy of defining your position can be reduced to approximately 1 m by utilizing a reference receiver on the ground that communicates with the satellites and then working out your position relative to the reference receiver, as shown in **Figure C.2**.

Global Positioning Systems are commonly linked to computers, so when a position is known, it may be plotted directly on a map viewed on a computer screen. GPS technology is revolutionizing the way we do our mapping, is becoming widely available, and is a valuable research tool in the field.

A word of information here concerning the term *in the field*. When geologists use the term *in the field*, we mean "outside on the surface on Earth" and are not referring to the "field of geology." For example, I am now about to go out and study the coastline of California after the El Niño storms. I would say to my colleagues, "I am going into the field."

An Example From A Coastal Landscape

A coastal landscape is shown in **Figure C.3** (page C-6). As illustrated in (a), which is an oblique view of the topography, the area is characterized by two hills with an intervening valley. A coastal seacliff is shown on the east (right) part of the diagram, and a sandspit produced by longshore coastal processes (see Chapter 10) with a hook on the end suggests that the direction of sand transport in the surf zone and beach is from the east (right) to the west (left) along this coastal area. A topographic map for the area is shown in (b). Notice that the contour interval (CI) is 20 ft. The elevation at the top of the highest hill on the east side of the diagram would be approximately 290 ft; because the last contour is 280, and the hill cannot be higher than 300, we split the difference. Several streams flow into the main valley; notice that the contours V in the upstream direction, particularly toward the peak of elevation of approximately 270 ft. Other information that may be "read" from the topographic map includes the following.

- The landform on the western portion of the map (left side) is a hill with elevation of about 275 ft and a gentle slope to the west, and a steep slope to the east (right) and toward the ocean. The eastern slope is particularly steep near the top of the mountain where the contours are very close together.
- The center part of the map shows a river flowing into a bay protected by a hooked sand bar. The

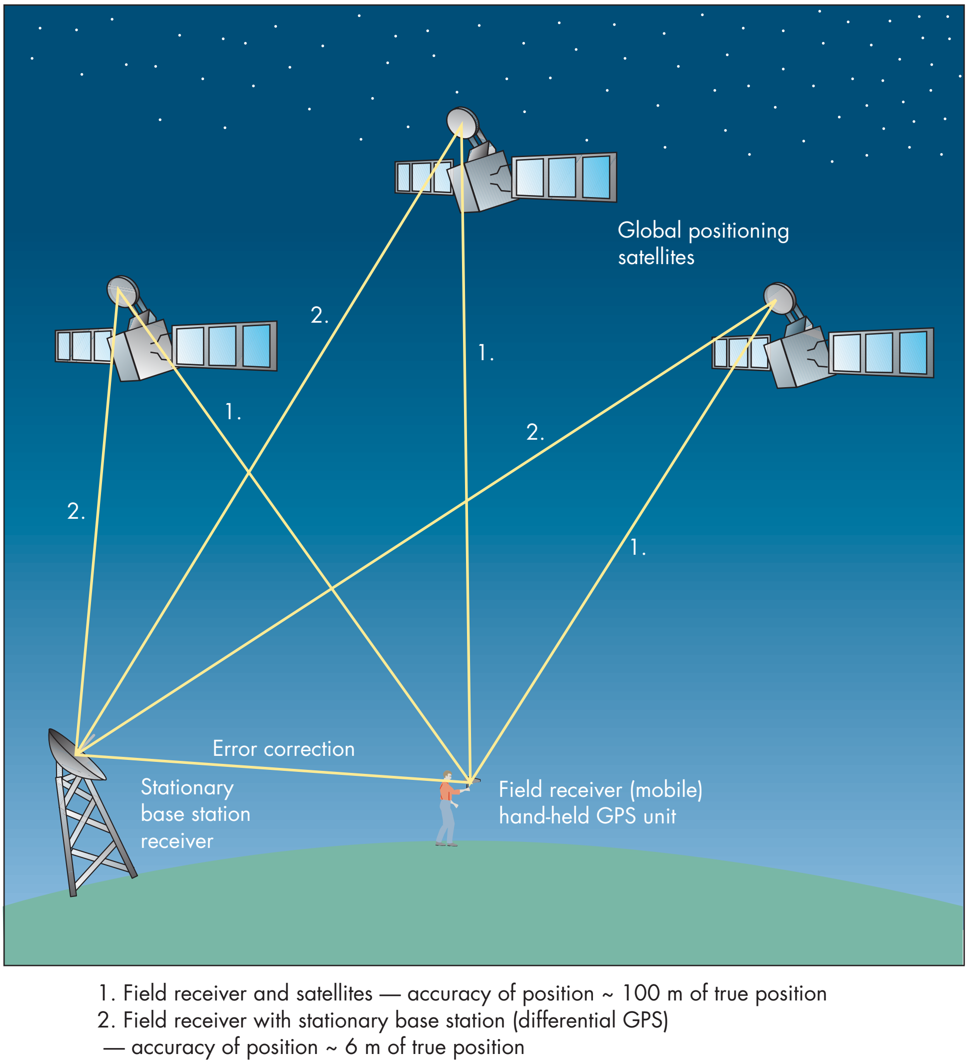


FIGURE C.2 Idealized diagram showing how GPS systems work.

relatively flat land in the vicinity of the river is a narrow floodplain with a light-duty road (see Figure C.3) delineated by two closely spaced lines extending along the western side. A second unimproved road crosses the river and extends out to the head of the sandspit, providing access to a church and two other buildings. The floodplain is delineated on both sides of the river by the 20-ft contour, above which the 40-ft contour is a break in slope at the edge of the valley.

- The eastern and southern slopes of the hill on the west (left) side of the map with elevation of about 275 ft have a number of small streams flowing mostly southward into the ocean. These streams may be defined as relatively steep gullies that are dissecting (eroding) the hill.
- In contrast to the hill on the western part of the map, the hill on the eastern part with elevation of approximately 290 ft has gentler slopes on the eastern flank, with streams spaced relatively far apart flowing toward the river and the ocean. Thus, we could state that the streams flowing to the main river valley from the east have dissected (eroded) the landscape more (to a lower slope) than those streams flowing into the main valley from the west.
- In particular, note the stream channel just south of the hill with elevation of about 275 ft on the west side of the map. That stream is actively eroding headward, forming a narrow, steep gully denoted by the pattern of closely spaced contours that form a concave indentation into the more gentle topography that forms the surface that is sloping to the west from the top of the mountain.

To continue a study of this area, we might construct more topographic profiles across the area from east to west and also construct profiles of some of the streams flowing into the main valley. The next

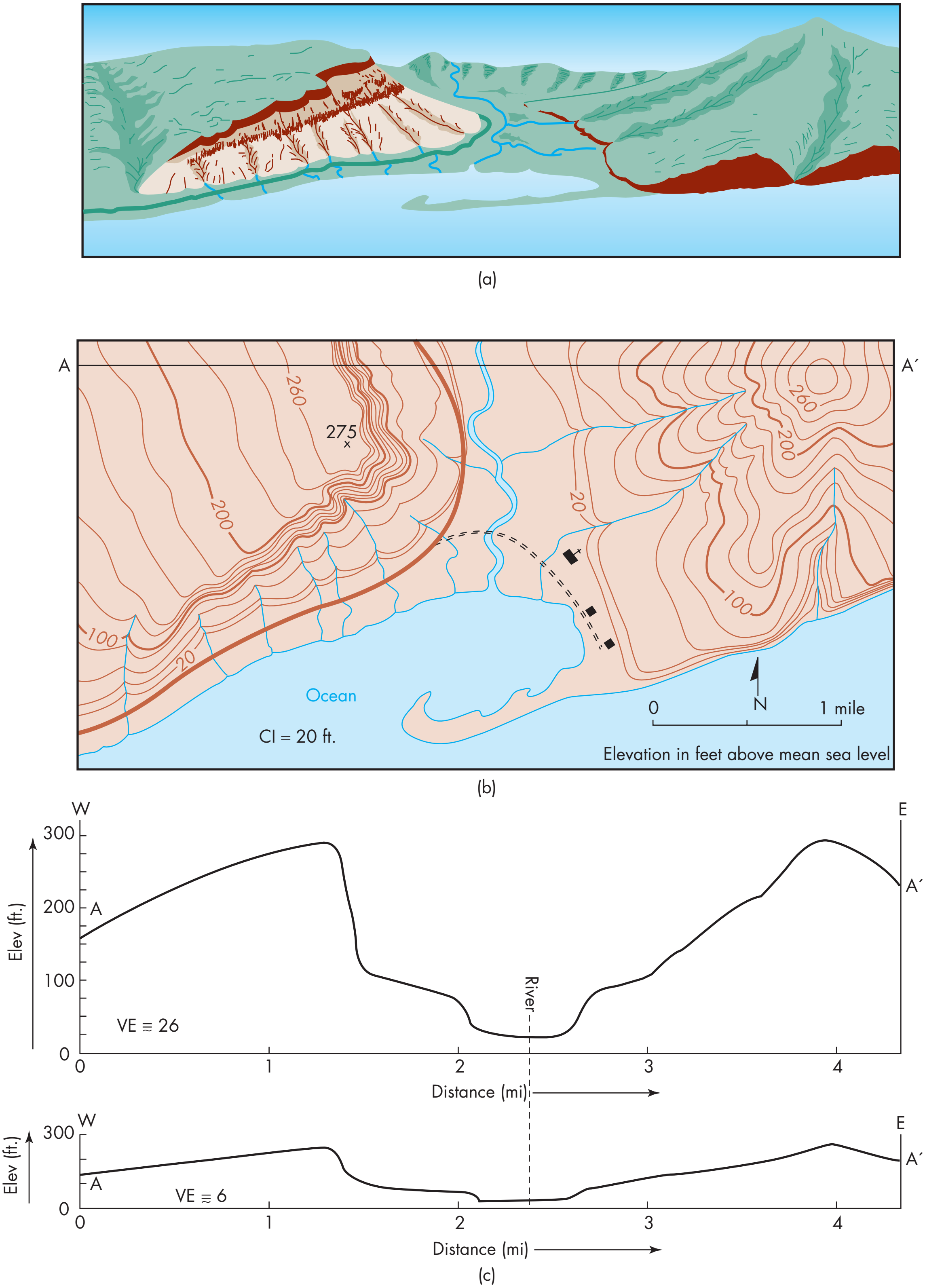


FIGURE C.3 Drawing of a landscape along a coastal area (a) Set of diagrams illustrating topographic maps. (b) Topographic map for the same area with a contour interval of 20 ft. (c) Topographic profiles along line T of the topographic map shown with vertical exaggeration of approximately 26 times and 8 times. The vertical exaggeration is the ratio of the vertical to horizontal scale of the topographic profile. The ratio for the upper profile is approximately 26, so we say that the vertical exaggeration is approximately 26 times. For the lower profile, the vertical exaggeration is about 8 times. In the real world, of course, there is no vertical exaggeration (the vertical and horizontal scales are the same). As an experiment, you might try to make a topographic profile along line T with no vertical exaggeration. What do you conclude? *(From U.S. Geological Survey)*

task might be to obtain aerial photographs and geologic maps to draw more conclusions concerning the topography and geology.

Geologic Maps

Geologists are interested in the types of rocks found in a particular location and in their spatial distribution. Producing a geologic map is a very basic step in understanding the geology of an area. Geologic maps are the fundamental database from which to interpret the geology of an area. The first step in preparing a geologic map is to obtain good base maps (usually topographic) or aerial photographs on which the geologic information may be transferred. The geologist then goes into the field and makes observations at outcrops where the rocks may be observed. Different rock types, units, or formations are mapped and the contacts between varying rock types are mapped as lines on the map. The attitude of sedimentary rock units is designated by a T-shaped strike and dip symbol. The strike is the compass direction of the intersection of the rock layer with a horizontal plain, and the dip is the maximum angle the rock layer makes with the horizontal (**Figure C.4**). **Figure C.5a** shows a very simple geologic map with three rock types—sandstone, shale, and limestone—over an area of approximately 1,350 km^2. The arrangement of the strike and dip symbols suggests that the major structure is an anticline. A geologic cross section constructed across the profile along the line E-E' is shown in Figure C.5b.

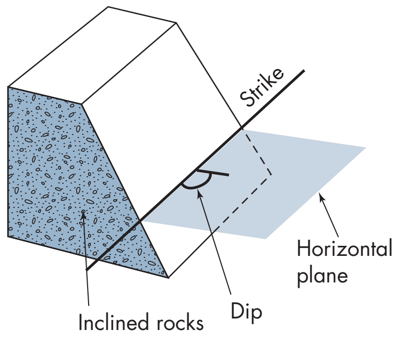


FIGURE C.4 Idealized block diagram showing the strike and dip of inclined sedimentary rocks.

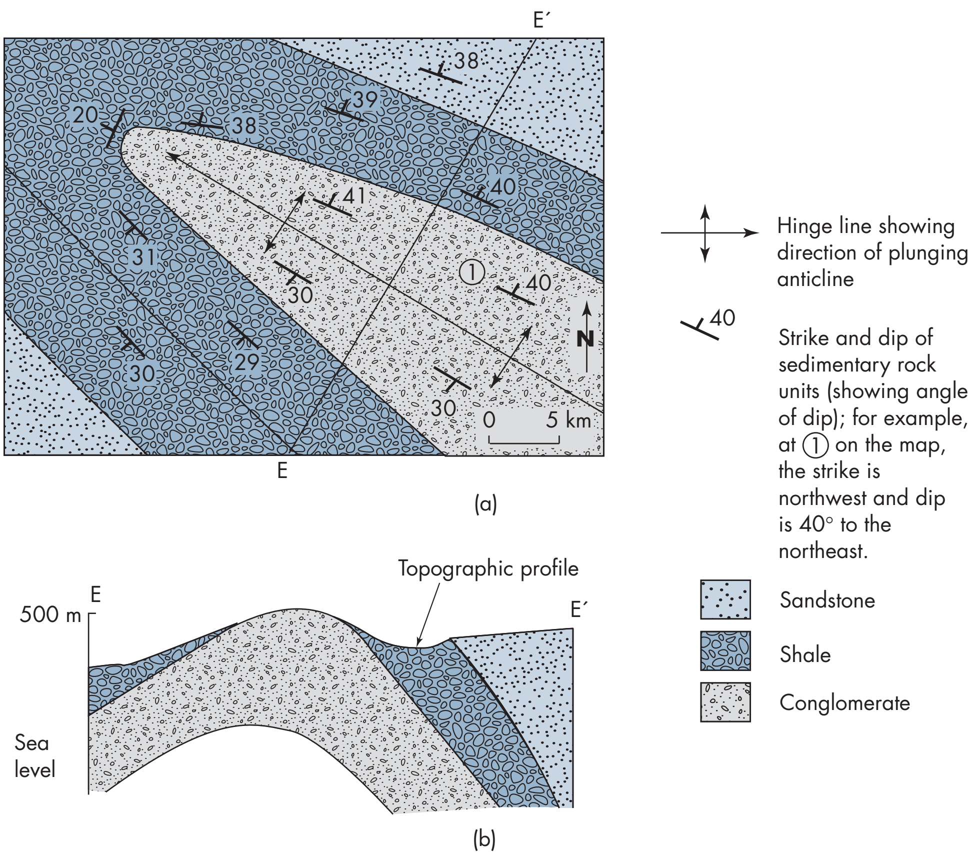


FIGURE C.5 (a) **Idealized diagram** showing a very simple geologic map with three rock types and (b) geologic cross section showing the topography and structure of the anticline.

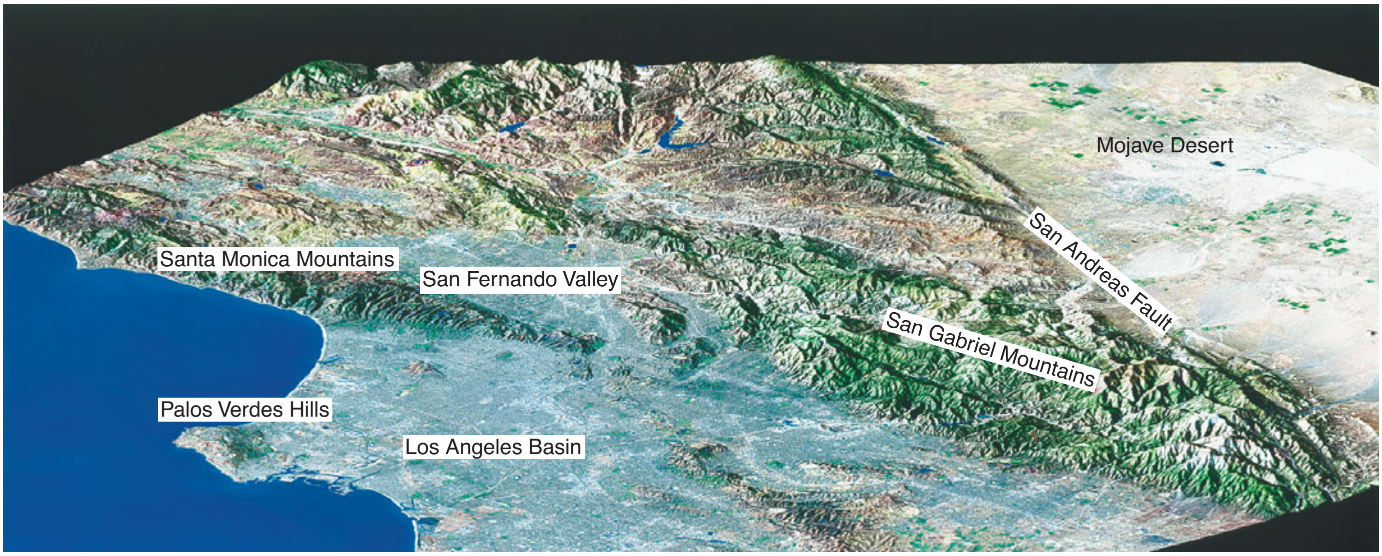


FIGURE C.6 Color relief map made from a Digital Elevation Model of the Los Angeles area with a fair amount of vertical exaggeration. The flat area in the central part of the image is the Los Angeles Basin. The smaller basin just to the left is the San Fernando Valley, which is separated from the Los Angeles Basin by the Santa Monica Mountains. *(Courtesy of Robert Crippin, NASA, Jet Propulsion Laboratory)*

Geologists often make a series of cross sections to try to better understand the geology of a particular area. Geologic maps at a variety of scales from 1 to 250,000 down to 1 to 24,000 are generally available from a variety of sources, including the U.S. Geological Survey.

Digital Elevation Models

Topographic data for many areas in the United States and other parts of the world are now available on computer disk. The arrays of elevation values, which may include, for example, the elevation of the ground on a 30 m $\times$ 30 m ground spacing grid (area, 900 m^2), are the basic topographic data. This is the Digital Elevation Model (DEM). Computer programs are then used to view the data, and color shading may be provided to show the topography, which is a DEM product. DEMs provide a visual representation of the surface of Earth and can be "viewed" from a variety of angles. That is, you may decide you would like to view the topography obliquely from the south, north, east, or west. The vertical dimension may also be exaggerated so that minor topographic differences may become more apparent. Figure C.6 shows a relief map constructed from a digital elevation model for the Los Angeles Basin. This clearly illustrates that Los Angeles is nearly surrounded by mountains and hills, which are uplifted by recent tectonic activity. DEMs are becoming important research tools in evaluating the topography of an area. They may be used to delineate and map such features as fault scarps, drainages, marine terraces, floodplains, and many other features of the landscape.

For detailed studies of a relatively small area DEMs may be constituted from high resolution data that has a horizontal spacing of elevation points of 1 m $\times$ 1 m where horizontal and vertical resolution is about 0.5 m. High resolution data can be obtained from Light Detection and Ranging (LiDAR) from an aircraft. There are now mobile LiDAR instruments that can gather topographic data from the ground in the field. Repeated LiDAR surveys over periods of 1–10 years can detect changes in landforms such as a retreating sea cliff or slow moving landslide.

Summary

Our discussion establishes that there are several types of maps that are useful in evaluating a particular area and its geology. Of particular importance are topographic maps and geologic maps. Digital elevation models may be constructed from topographic data, and a variety of other special purpose maps are also available. Examples include maps of recent landslides, maps of floodplains, and engineering geology maps that show engineering properties of earth materials.

Appendix D

How Geologists Determine Geologic Time

In order to understand the history of Earth, we have to determine the actual age of rocks and sediments. The science of dating rocks and sediments is known as **geochronology**. Although it is possible to establish relative geochronology based upon fossil evidence using the law of faunal assemblages and geologic relationships such as the laws of superposition and crosscutting relationships (see Chapters 1 and 3), it is absolute dating (numerical dating), that provides the geochronology necessary to establish rates of geologic processes and ages of rocks. The science of geochronology is expanding rapidly and includes a number of techniques that provide numerical ages from a few years to a few billion years (the age of Earth).

From an environmental perspective, it is important to be able to establish rates of geologic processes and when geologic events such as volcanic eruptions, earthquakes, floods, and landslides occurred in the past. The chronology of natural hazard events is critical in establishing their return period as part of better understanding hazards and predicting when they are likely to occur in the future. That is, we wish to establish rates of geologic processes of significance to society.

Geologic time is much different, in a way, than our normal time framework. Although geologic time and "normal" time use the same units of measure—years—they differ vastly in duration and in the instruments we use to measure duration.[1] Normal time is counted in hours, days, seasons, or decades, and the instrument used to measure time is a clock. For "deep time" (geologic time), measured in millions to hundreds of millions to several billion years, geologists take advantage of naturally occurring isotopes such as uranium-235, uranium-238, potassium-40, or carbon-14 to date the rocks in which these isotopes occur. Dating is possible because the natural decay of each type of unstable radioactive isotope occurs at a constant rate that can be used to determine the age of rocks in which that isotope occurs. The process of radioactive decay is a spontaneous process in which the nucleus of a particular isotope undergoes a change while emitting one or more forms of radiation (see Chapter 16, A Closer Look: Radioactivity). The three major kinds of radiation that are emitted during radioactive decay are called alpha particles, beta particles, and gamma radiation. Alpha decay is particularly significant because the decay consists of two protons and two neutrons. The isotope present before alpha decay is known as the parent, and the new isotope present after decay is known as the daughter product, which is an isotope of a different element. Radioactive isotopes, particularly those of very heavy elements, undergo a series of radioactive decay steps that finally ends when a stable, nonradioactive isotope is produced. For example, uranium-238 undergoes 14 nuclear transformations emitting alpha, beta, and gamma radiation in different steps to finally decay to stable lead-206, which is not radioactive. An important characteristic of a radioisotope such as U-238 is its half-life, which is the time required for one-half of a given amount of the isotope to decay to another form. Every radioisotope has a unique and characteristic half-life. **Table D.1** shows four parent radioactive isotopes, their daughter stable isotopes, and characteristic half-lives. **Figure D.1** shows in diagrammatic form the reduction of a parent radioactive isotope and concurrent increase in the daughter product. For example, after one half-life, 50 percent of the original parent isotope remains; this is reduced to 25 percent after two half-lives, and to 12.5 percent after three half-lives. By the time six half-lives have nearly passed, all the parent material has been lost through radioactive decay. As the parent material decreases, the daughter product increases to be nearly 100 percent by six half-lives. Because the

TABLE D.1 Parent and Daughter Isotopes with Half-Lives for Four Elements Commonly Used to Absolutely (Numerically) Date Earth Materials Such as Rock or Organic Material

Parent Radioactive Isotopes	Daughter Stable Isotope	Half-Life
Uranium-238	Lead-206	4.5 billion yr
Uranium-235	Lead-207	700 million yr
Potassium-40	Argon-40	1.3 billion yr
Carbon-14	Nitrogen-14	5,730 yr

process of radioactive decay is irreversible and occurs at a constant rate, it serves as a clock that may be used for absolute (numerical) age dating in years. Because radioisotopes such as uranium-238, uranium-235, and potassium-40 have relatively long half-lives (Table D.1), their decay is useful in dating rocks on the order of millions to billions of years. For example, radioactive uranium has been used to date the oldest rocks on Earth at about 4.6 billion years before present. The actual methods of measuring amounts of parent and daughter isotopes and calculating numeric dates are complex and tedious, although the concept is easy to grasp. These methods have been used successfully to develop the geochronology necessary to place numerical dates in the geologic time table and to delineate important Earth history events such as mountain building, ice ages, and the appearance of life forms.

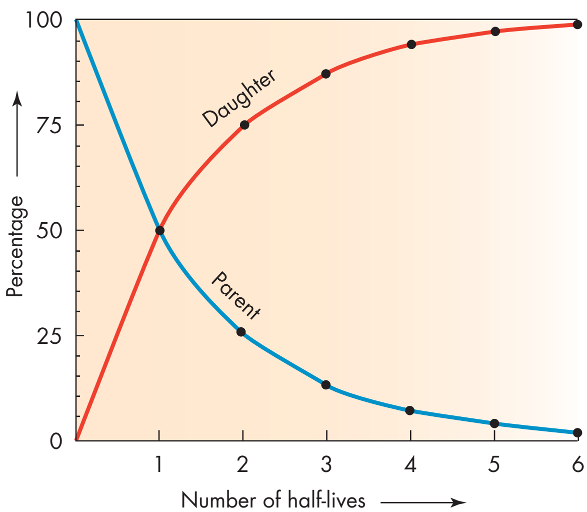


FIGURE D.1 Reduction of a parent radioactive isotope to a daughter isotope with increasing half-lives.

Archeologists and anthropologists concerned with human history are interested in developing a geochronology with a duration of a few million years or less, that is the period from which human and ancestral human fossils are found. From an environmental geology perspective, we are often interested in establishing the geochronology of the past few hundred to few hundred thousand years of Earth's history, and for this we have several potential methods. For example, the radioisotope uranium-234 undergoes radioactive decay at a known rate to thorium-230, and the ratio of these two isotopes is useful in numerically dating a variety of materials, such as coral, back to several hundred thousand years. For sediments younger than about 40,000 years, carbon-14 is used extensively for numerical dating. The most common form of carbon is stable carbon-12, but carbon-14, which is radioactive, occurs in small quantities and undergoes radioactive decay to the stable daughter isotope nitrogen-14. The half-life of the decay of carbon-14 to nitrogen-14 is 5,730 years. The carbon-14 method works because organic material incorporates carbon-14 into living tissue, and when the organism dies radioactive decay begins. Common materials dated by carbon-14 include wood, bone, charcoal, and other types of buried organic material. Carbon-14 has a relatively short half-life, and, as a result, after about 40,000 years the amount of carbon-14 remaining is very small and difficult to measure. Consequently, use of this technique is limited.

The field of geochronology is expanding rapidly, and new techniques are being developed as I write this. For example, it is now possible to directly date the duration that a landform has been exposed at Earth's surface. This is known as exposure dating. The basic idea is that certain isotopes—for example, beryllium-10, aluminum-26, and chlorine-36—that

are produced when cosmic rays interact with Earth's atmosphere, accumulate in measurable quantities in surface materials such as soils, alluvial deposits, and exposed rock surfaces. Thus, the amount of accumulation of these isotopes is a measure of the minimum time of exposure to the surface environment.

Other innovative methods of developing the geochronology of an area are also being used. For example, lichens, which are mosslike plants that grow on rock surfaces, are known to have given growth rates for particular species, and they tend to grow in circular patches. Careful measurements of the size of lichen patches, coupled with known growth rates, provide minimum numerical ages for the rocks they are found on. The method has been successfully used in California and New Zealand to date regional occurrences of rockfalls generated by large earthquakes, thus dating past seismic activity.[2,3] Lichenometry can provide dates to about 1,000 years before present. Sediments may also be accurately dated through the use of dendrochronology, which is the analysis of annual growth rings to measure the age of woody material found in sediments. The method has been used extensively by archeologists to date prehistoric sites of human habitation and also by climatologists as a method of reconstructing past climates in terms of wet and dry years. Growth rings record climate because during dry years tree rings are narrow relative to wet years. Very accurate numerical geochronology may also be obtained from counting varves. A varve is a layer of sediment representing one year of deposition, usually in a lake or an ocean. Careful counting of varves may extend the chronology back several thousand years.

The most accurate chronology is the historical record, but in many parts of the world the historical record is only a few hundred years (as for example, in the United States). In other areas, such as China, the historical record extends several thousand years. However, given the brevity of human history compared with the great length of geologic history, we resort to numerical dating methods to establish geochronology. There are more than 20 methods useful in establishing geochronology that yield numerical dates. This discussion presents only a few of these at a very elementary level. The science of geochronology is complex but extremely crucial to understanding rates of geologic processes and placing geologic events in chronological order.

References

1. **Ausich, W. I., and Lane, G. N.** 1999. *Life of the past,* 4th ed. Upper Saddle River, NJ: Prentice Hall.
2. **Bull, W. B., and Brandon, M. T.** 1998. Lichen dating of earthquake-generated regional rock fall events. Southern Alps, New Zealand. *Geological Society of America Bulletin* 110(1):608–684.
3. **Bull, W. B.** 1996. Dating San Andreas fault earthquakes with lichenometry. *Geology* 24: 111–114.

Appendix E

Darcy's Law

In 1856 an engineer named Henry Darcy was working on the water supply for Dijon, France. He performed a series of important experiments that demonstrated that the discharge (Q) of groundwater may be defined as the product of the cross-sectional area of flow (A), the hydraulic gradient (I), and the hydraulic conductivity (K). Thus,

$$Q = KIA$$

The unit on each side of the equation is a volumetric flow rate (such as cubic meters per day), and the relationship is known as **Darcy's law**. The quantity $Q/A = KI$ is the **Darcy flux** (v). We may say that

$$v = Q/A \quad \text{or} \quad Q = vA$$

Although v has the unit of a velocity, the Darcy flux is only an apparent velocity. To determine the actual velocity of groundwater in an aquifer (vx) we must remember that the water moves through pore spaces, so its velocity is affected by the porosity of the aquifer material. If we let n represent the porosity, then the actual cross-sectional area of flow is An, and it follows from $Q = vA$ that

$$vx = Q/An = v/n \quad \text{or} \quad vx = KI/n$$

The actual velocity vx is about three times the Darcy flux (assuming an average value of $n = 0.33$).

The driving force for groundwater flow is called the **fluid potential** or **hydraulic head,** which at the point of measurement is the sum of the elevation of the water (elevation head) and the ratio of the fluid pressure to the unit weight of water (pressure head). The difference in hydraulic heads between two points (h) divided by the flow length (L) gives us the hydraulic gradient (I).

Groundwater always moves from an area of higher hydraulic head to an area of lower hydraulic head and may therefore move down, laterally, or upward, depending upon local conditions.

Darcy's law has many important applications to groundwater problems. For example, consider an area underlain by sedimentary rocks with a semiarid climate. The area is dissected by a river system in a valley approximately 4 km wide. Alluvial deposits in the valley form an aquifer confined by a clay layer, and two wells have been drilled approximately 1 km apart in the down-valley direction (**Figure E.1a**). A cross-valley section between the wells (Figure E.1b) shows that the saturated zone is 25 m thick, consists of sand and gravel, and has a hydraulic conductivity of 100 m/day (1.2×10^{-3} m/sec). Porosity (n) of the aquifer materials is 30 percent (0.3). A down-valley section is shown in Figure E.1, part c. The wells are separated by 1,000 m and the elevation of the water in wells 1 and 2 are, respectively, 98 m and 97 m. Two questions we might ask concerning the conditions shown in Figure E.1 are

1. What is the discharge Q (m^3/sec or gallons per day) of water moving through the aquifer in the down-valley direction?
2. What is the travel time (T) of the groundwater between wells 1 and 2? This question is particularly interesting from an environmental standpoint if a water pollution event is detected at well 1 and we want to know when the pollution will reach well 2.

Answering these two questions requires us to apply Darcy's law to the situation outlined above. To answer the first question, which asks how much water is moving through the aquifer, recall that $Q = KIA$. We will solve for Q. The hydraulic gradient is the ratio of the difference in elevation of the water (pressure head) between the two wells to the length of the groundwater flow between the wells. The difference in elevation of the water in wells 1 and 2 is 1 m and the flow length is 1,000 m. Thus, the hydraulic gradient (I) is 0.001 (1×10^{-3}). The hydraulic conductivity is given as 1.2×10^{-3} m/sec. The cross-sectional area of the aquifer (A) is 25 m $\times$ 4,000 m, or 100,000 m^2 (1×10^5 m^2). Multiplying these numbers, we find that Q is equal to 0.12 m^3/sec. This is equivalent to 10,368 m^3/day, which is approximately 2.7 million gallons per day. Of course, all of this water could not

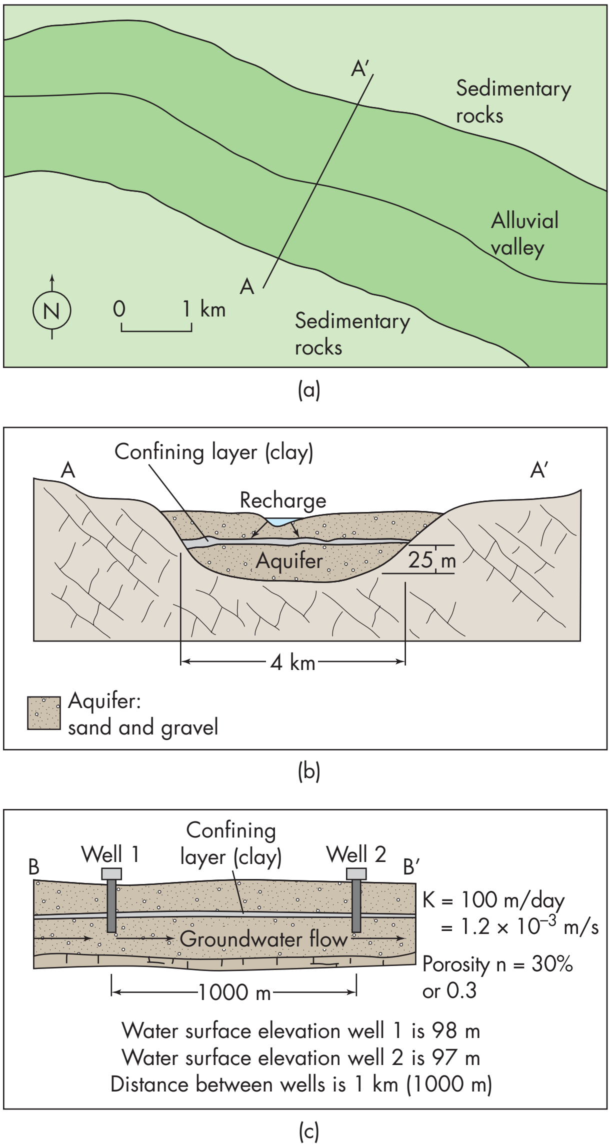


FIGURE E.1 Hypothetical map of an alluvial valley
(a) Cross-valley profile. (b) Profile down-valley. (c) Showing groundwater conditions.

be pumped from the aquifer. Pump tests of the wells would be necessary to determine how much of the 2.7 million gallons per day could be pumped without depleting the resource.

Turning now to the second question, which concerns the travel time of the water from one well to the other, we again apply Darcy's law. In this case we calculate the Darcy flux (v), which is

$$v = Q/A = KI$$

Remember that the Darcy flux is only an apparent velocity and does not reflect the fact that the actual movement of the groundwater is through the pore spaces between the grains of sand and gravel in the aquifer. The actual velocity (vx) is the ratio of the product of KI to the porosity.

$$\begin{aligned} vx &= KI/n \\ &= (1.2 \times 10^{-3}\,\text{m/sec})(1 \times 10^{-3})/0.3 \\ &= 4.0 \times 10^{-6}\,\text{m/sec} \end{aligned}$$

Travel time (T) then is the ratio of the length of flow (L) to the velocity of the water moving through the pore spaces (vx). This follows from the fact that distance L is the product of velocity vx and time T, ($L = vxT$). Thus, $T = 1{,}000\ \text{m}/(4.0 \times 10^{-6}\ \text{m/sec}) = 2.5 \times 10^{8}$ sec. This is approximately 7.9 years.

Glossary

A soil horizon Uppermost soil horizon, sometimes referred to as the zone of leaching.

Abrasion With respect to wind processes, refers to the erosion of rock surfaces as the result of collision of sand or silt grains being transported by the wind colliding with rock surfaces to cause pitting or polishing.

Absorption The process of taking up, incorporating, or assimilating a material.

Acid mine drainage An environmental problem related to the discharge of acidic waters resulting from the weathering of sulfide minerals, such as iron pyrite, associated with coal and sulfide mineralization of important metals, such as copper, silver, and zinc.

Acid rain Rain made artificially acidic by pollutants, particularly oxides of sulfur and nitrogen; natural rain water is slightly acidic owing to the effect of carbon dioxide dissolved in the water.

Active fault There are a variety of definitions, but one is displacement along a fault in the past 10,000 years; another definition is multiple displacements in the past 35,000 years.

Active method With respect to permafrost, refers to the method of thawing the frozen ground before constructing buildings and other structures; generally used when permafrost is thin or discontinuous.

Adaptive management Application of science to management of environmental projects such as restoration. An ongoing process that includes evaluation and monitoring that allows for change as conditions dictate during and after the project.

Adsorption Process in which molecules of gas or molecules in solution attach to the surface of solid materials with which they come into contact.

Advanced treatment With respect to wastewater treatment, includes a variety of processes, such as use of chemicals, sand filters, or carbon filters to further purify and remove contaminants from wastewater.

Aerobic Characterized by the presence of free oxygen.

Aesthetics Originally a branch of philosophy, defined today by artists and art critics.

Aftershocks Earthquakes that occur a few minutes to a few months to a year or so after the main event.

Agglomerate volcanic breccia *See* Volcanic breccia, agglomerate.

Aggregate Any hard material, such as crushed rock, sand, gravel, or other material that is added to cement to make concrete.

Air Quality Index Method by which air quality in urban areas is usually reported, defining levels or stages of air pollution in terms of the National Ambient Air Quality Standards.

Air Quality Standards Levels of air pollutants that define acceptable levels of pollution generally over a particular time period.

Air toxin Air pollutant known to cause cancer or other serious health conditions.

Albedo A measure of reflectivity or the amount (by decimal or percent) of electromagnetic radiation reflected by a material or surface.

Alkaline soil Soil found in arid regions that contains a large amount of soluble mineral salts (primarily sodium) that in the dry season may appear on the surface as a crust or powder.

Alluvial fan A fan-shaped deposit that is a segment of a cone that forms where a stream emerges from a mountain front; sediments deposited include stream flow deposits and mudflow or debris deposits.

Alluvium Unconsolidated sediments, including sand, gravel, and silt, deposited by streams.

Alpha particles Type of nuclear radiation consisting of two protons and two neutrons emitted during radioactive decay.

Alternative energy Refers to energy sources that are alternative to the commonly used fossil fuels.

Anaerobic Characterized by the absence of free oxygen.

Andesite A type of volcanic rock consisting of feldspar and other silicate minerals rich in iron and magnesium with an intermediate silica content of about 60 percent; an example is Mount Fuji in Japan.

Angle of repose The maximum angle that loose material will sustain.

Anhydrite Evaporite mineral ($CaSO_4$) calcium sulfate.

Anthracite A type of coal characterized by a high percentage of carbon and low percentage of volatiles, providing a high heat value; often forms as a result of metamorphism of bituminous coal.

Anticline Type of fold in rock characterized by an upfold or arch; the oldest rocks are found in the center of the fold.

Appropriation doctrine, water law Holds that prior usage of water is a significant factor; the first to use the water for beneficial purposes is prior in right.

Aquiclude Also known as aquitard; earth material that will hold groundwater but cannot transmit it at a rate sufficient to be pumped from a well. *See* Impermeable.

Aquifer Earth material containing sufficient groundwater that the water can be pumped out; highly fractured rocks and unconsolidated sands and gravels make good aquifers.

Aquitard Earth material that retards the flow of groundwater.

Area source Type of nonpoint air or water pollution that is diffused, such as runoff from an urban area or automobile exhaust.

Area (strip) mining Type of strip mining practiced on relatively flat areas.

Argillic B soil horizon Designated as *Bt*, a soil horizon enriched in clay minerals that have been translocated downward by soil-forming processes.

Arid Refers to regions with an annual precipitation less than approximately 25 cm/yr.

Artesian Refers to a groundwater system in which the groundwater is isolated from the surface by a confining layer and the water is under pressure. Groundwater that is under sufficient pressure will flow freely at the surface from a spring or well.

Asbestos Fibrous mineral material used as insulation. It is suspected of being either a true carcinogen or a carrier of carcinogenic trace elements.

Ash, volcanic Unconsolidated volcanic debris, less than 4 mm in diameter, physically blown out of a volcano during an eruption.

Ash fall Volcanic ash eruption that blows up into the atmosphere and then rains down on the landscape.

Ash flow Mixture of volcanic ash, hot gases, and fragments of rock and glass that flows rapidly down the flank of a volcano; may be an extremely hazardous event.

Asteroid Rock or metallic particle in space from about 10 m to 1,000 km in diameter.

Asthenosphere The upper zone of Earth's mantle, located directly below the lithosphere; a hot, slowly flowing layer of relatively weak rock that allows for the movement of the tectonic plates.

Atmosphere Layer of gases surrounding Earth.

Atmospheric inversion When warm air overlies cool air in the lower atmosphere.

Atom The smallest part of a chemical element that can take part in a chemical reaction or combine with another element.

Avalanche A type of landslide involving a large mass of snow, ice, and rock debris that slides, flows, or falls rapidly down a mountainside.

Average residence time The amount of time it takes for the total stock or supply of material in a system to be cycled through the system.

B soil horizon Intermediate soil horizon; sometimes known as the *zone of accumulation*.

Balance of nature The idea that nature undisturbed by human activity will reach a balance or state of equilibrium; is thought by some to be an antiquated idea that probably has never existed in nature.

Barrier island Island separated from the mainland by a salt marsh; generally consists of a multiple system of beach ridges and is separated from other barrier islands by inlets that allow exchange of seawater with lagoon water.

Basalt A type of volcanic rock consisting of feldspar and other silicate minerals rich in iron and magnesium; has a relatively low silica content of about 50 percent; the most common volcanic rock-forms of shield volcanoes.

Basaltic Engineering geology term for fine-grained igneous rocks.

Base flow The low flow discharge of a stream or river, which is produced by groundwater seeping into the channel.

Base level The theoretical lowest elevation to which a river may erode; generally is at or about sea level.

Batholith A large intrusion of igneous rock that may exceed thousands of cubic kilometers generally with surface expression greater than 100 km^2; commonly composed of several intrusions known as *plutons*.

Bauxite A rock composed almost entirely of hydrous aluminum oxides; a common ore of aluminum.

Beach Accumulation of whatever loose material (commonly sand, gravel, or bits of shell and so forth) that accumulate on a shoreline as the result of wave action.

Beach budget Inventory of sources and losses of sediment to a particular stretch of coastline.

Beach face That part of the beach environment that is a nearly planar part of the beach profile below the berm and normally exposed to the swash action from waves.

Beach nourishment Artificial process of adding sediment (sand) to a beach for recreational and aesthetic purposes as well as to provide a buffer to coastal erosion.

Bedding plane The plane that delineates the layers of sedimentary rocks.

Bed load That portion of the total load that a stream carries that moves along the bottom of the channel by rolling, sliding, or skipping.

Bed material Sediment transported and deposited along the bed of a stream channel.

Bentonite A type of clay that is extremely unstable; when wet, it expands to many times its original volume.

Berm The relatively flat part of a beach profile produced by deposition from waves; the part of the beach where people sunbathe.

Beta particles Type of nuclear radiation consisting of electrons emitted during radioactive decay.

Biochemical oxygen demand (BOD) A measure of the amount of oxygen necessary to decompose organic materials in a unit volume of water. As the amount of organic waste in water increases, more oxygen is used, resulting in a higher BOD.

Biodiversity In general, refers to the variety of life in an area, region, or Earth. Also refers to the total number of species (richness) or the main species encountered (dominance).

Biofuel A number of fuels, including ethanol (alcohol), derived from plants.

Biogeochemical cycle Movement of a chemical element or compound through the various Earth systems including atmosphere, lithosphere, biosphere, and hydrosphere.

Bioleaching Use of microorganisms to recover metals, as for example release of finely disseminated gold that may then be treated by cyanide leaching.

Biomagnification The process whereby chemicals may accumulate at higher and higher concentrations in the food chain; also referred to as biological concentration.

Biomass Organic matter. As a fuel, biomass can be burned directly (as wood) or converted to a more convenient form (such as charcoal or alcohol) and then burned.

Biopersistence A measure of how long a particular material will remain in the biosphere.

Bioremediation With respect to soil pollution, refers to technology that utilizes natural or enhanced microbial action in the soil to degrade organic contaminants *in situ* (at the site), not requiring excavation of the soil.

Biosphere The zone adjacent to the surface of Earth that includes all living organisms.

Biotechnology With respect to resource management, refers to use of organisms to assist in mining of ores or cleaning up of waste from mining activities.

Biotite A common ferromagnesian mineral, a member of the mica family.

Bituminous coal A common type of coal characterized by relatively high carbon content and low volatiles; sometimes called *soft coal*.

Bk soil horizon Soil horizon characterized by accumulation of calcium carbonate that may coat individual soil particles and fill some pore spaces but does not dominate the morphology of the horizon.

Blowout Failure of an oil, gas, or disposal well resulting from adverse pressures that can physically blow part of the well casing upward; may be associated with leaks of oil, gas, or, in the case of disposal wells, harmful chemicals.

Braided river A river channel characterized by an abundance of islands that continually divide and subdivide the flow of the river.

Breaker zone That part of the beach and nearshore environment where incoming waves peak up, become unstable, and break.

Breakwater A structure (as a wall), which may be attached to a beach or located offshore, designed to protect a beach or harbor from the force of the waves.

Breccia A rock or zone within a rock composed of angular fragments; sedimentary, volcanic, and tectonic breccias are recognized.

Breeder reactor A type of nuclear reactor that produces more fissionable fuel than it consumes.

Brine Water that has a high concentration of salt.

British thermal unit (Btu) A unit of heat defined as the heat required to raise the temperature of 1 lb of water 1°C.

Brittle Material that ruptures before any plastic deformation.

Burner reactor Type of nuclear reactor used to generate electricity that consumes more fissionable material than it produces.

C soil horizon Lowest soil horizon, sometimes known as the zone of partially altered parent material.

Calcite Calcium carbonate ($CaCO_3$); common carbonate mineral that is the major constituent of the rock limestone; weathers readily by solutional processes; large cavities and open weathered fractures are common in rocks that contain calcite.

Caldera Giant volcanic crater produced by very rare but extremely violent volcanic eruption or by collapse of the summit area of a shield volcano after eruption.

Caldera eruption Relatively infrequent large volcanic eruption that is associated with a catastrophic explosion that may produce a very large volcanic crater 30 or more kilometers in diameter.

Caliche A white-to-gray irregular accumulation of calcium carbonate in soils of arid regions.

Calorie The quantity of heat required to raise the temperature of 1 g of water from 14.5° to 15.5°C.

Cambic soil horizon Soil horizon diagnostic of incipient soil profile development, characterized by slightly redder color than the other horizons.

Capacity A measure of the total load a river may carry.

Capillary action The rise of water along narrow passages, facilitated and caused by surface tension.

Capillary fringe The zone or layer above the water table in which water is drawn up by capillary action.

Capillary water Water that is held in the soil through capillarity.

Carbon-14 Radioactive isotope of carbon with a half-life of approximately 5740 years; used in radiocarbon dating of materials back to approximately 40,000 years.

Carbonate A compound or mineral containing the radical CO_3. The common carbonate is calcite.

Carbon cycle One of Earth's major biogeochemical cycles that involves the movement of carbon in the atmosphere, biosphere, lithosphere, and hydrosphere.

Carbon monoxide (CO) A colorless, odorless gas that at low concentration is very toxic to humans and other animals; anthropogenic component of emissions is only about 10 percent and comes mainly from fires, automobiles, and other sources of incomplete burning of organic compounds; many people have accidentally been asphyxiated by carbon monoxide from poorly ventilated campers, tents, and homes.

Carcinogen Any material known to produce cancer in humans or other animals.

Carrying capacity The maximum number of a population of a species that may be maintained within a particular environment without degrading the ability of that environment to maintain that population in the future.

Catastrophe An event or situation causing sufficient damage to people, property, or society in general from which recovery and/or rehabilitation is long and involved; natural processes most likely to produce a catastrophe include floods, hurricanes, tornadoes, tsunamis, volcanoes, and large fires.

Cave A natural subterranean void that often consists of a series of chambers that are large enough for a person to enter, most commonly formed in the rock types limestone or marble.

Chain reaction With respect to nuclear fission, refers to the splitting of atomic nuclei by neutron bombardment that results in splitting of uranium and release of ever-more neutrons; such an action uncontrolled is the kind observed in nuclear explosions, whereas sustained stable reactions are those that occur in nuclear fission reactors that produce electricity.

Channelization An engineering technique to straighten, widen, deepen, or otherwise modify a natural stream channel.

Channel pattern The shape of a river channel as viewed from above ("bird's-eye view"); patterns include straight, meandering, and braided.

Channel restoration The process of restoring stream channels and adjacent areas to a more natural state.

Chemical bonding The holding together of atoms by attractive forces between atoms and/or sharing of electrons.

Cinder cone A volcanic, conical hill formed by the accumulation of volcanic ash and other pyroclastic deposits.

Circum-Pacific belt One of the three major zones where earthquakes occur; essentially the border of the Pacific plate; also known as the *ring of fire*, as many active volcanoes are found on the edge of the Pacific plate.

Clay May refer to a mineral family or to a very fine-grained sediment; associated with many environmental problems, such as shrinking and swelling of soils and sediment pollution.

Clay skins Oriented plates of clay minerals surrounding soil grains and filling pore spaces between grains.

Climate The characteristic atmospheric condition (weather) at a particular place or region over time periods of seasons, years, or decades.

Climate forcing An imposed perturbation of Earth energy balance. Major climatic forcings associated with global warming include: greenhouse gases, such as carbon dioxide and methane; reflective aerosols in the atmosphere; and black carbon. Forcing of the climate system also includes solar activity and Milankovitch Cycles.

Closed system A system with boundaries that restrict the flow of energy and matter; for example, with respect to mineral resources, Earth can be considered a closed system.

Coal A sedimentary rock formed from plant material that has been buried, compressed, and changed.

Coal-bed methane Methane stored on surfaces of organic matter in coal.

Coastal erosion Erosion of a coastline caused by a number of processes, including wave action, landsliding, wind, and runoff from the land.

Cogeneration With respect to energy resources, the recycling of waste heat to increase the efficiency of a typical power plant or factory; may involve production of electricity as a by-product from industrial processes.

Cohesion With respect to engineering properties of soils, refers to electrostatic forces that hold fine soil grains together and constitute a part of the shear strength of a soil.

Colluvium Mixture of weathered rock, soil, and other, usually angular, material on a slope.

Columnar jointing System of fractures (joints) that break rock into polygons of typically five or six sides; the polygons form columns; common in basalt and most likely caused by shrinking during cooling of the lava.

Comet Particle in space composed of a rocky core surrounded by ice from a few m to a few hundred km in diameter.

Common excavation Excavation that can be accomplished with an earthmover, backhoe, or dragline.

Competency A measure of the largest sized particle that a river may transport.

Complex response Mechanism of operation of a system in which changes occur at a variety of scales and times without input of multiple perturbations from outside the system.

Composite volcano Steep-sided volcanic cone produced by alternating layers of pyroclastic debris and lava flows.

Composting A biochemical process in which organic materials are decomposed to a humuslike material by aerobic organisms.

Compound In chemistry, any substance that contains more than one element of definite proportions by weight.

Comprehensive plan Planning document adopted by local governments that states general and long-range policies for how the community plans to deal with future development.

Compressibility (soil) Measure of a soil's tendency to decrease in volume.

Concentration factor With respect to mining of resources, the ratio of a metal's necessary concentration for profitable mining to its average concentration in Earth's crust.

Conchoidal fracture Fracture in rock or mineral that is smoothly curved, like a seashell.

Cone of depression A cone-shaped depression in the water table caused by withdrawal of water at rates greater than those at which the water can be replenished by natural groundwater flow.

Confined aquifer An aquifer that is overlain by a confining layer (aquitard).

Conglomerate A detrital sedimentary rock composed of rounded fragments, 10 percent of which are larger than 2 mm in diameter.

Conservation Policy for resources such as water and energy that moderates or adjusts demands in order to minimize expenditure of the resource; may mean getting by with less through improved technology to provide just the amount of the resource necessary for a given task.

Consumptive use A type of offstream use in which the water does not return to the stream or groundwater resource after use; the water evaporates, is incorporated into crops or products, or is consumed by animals or humans.

Contact metamorphism Type of metamorphism produced when country rocks are in close contact with a cooling body of magma below the surface of Earth.

Continental drift Movement of continents in response to seafloor spreading; the most recent episode of continental drift supposedly began about 200 million years ago with the breakup of the supercontinent Pangaea.

Continental shelf Relatively shallow ocean area between the shoreline and the continental slope that extends to approximately a 600-ft water depth surrounding a continent.

Continuity equation With respect to hydrology of rivers, refers to the equation that the discharge of flow is equal to the product of the cross-sectional area of flow times the velocity of the flow.

Contour (strip) mining Type of strip mining used in hilly terrain.

Contour plowing Practice of plowing the land along natural contours perpendicular to the downslope direction to reduce erosion.

Convection Transfer of heat involving movement of particles; for example, the boiling of water, in which hot water rises to the surface and displaces cooler water that moves toward the bottom.

Convergence of wave normals With respect to coastal processes, refers to areas where wave heights are higher and potential erosive power of waves are greater due to offshore topography or other features that concentrate the wave energy.

Convergent boundary Boundary between two lithospheric plates in which one plate descends below the other (subduction).

Core With respect to the interior of Earth, the central part of Earth below the mantle, divided into a solid inner core with a radius of approximately 1300 km and a molten outer core with a thickness of about 2000 km; the core is thought to be metallic and composed mostly of iron.

Corrosion A slow chemical weathering or chemical decomposition that proceeds inward from the surface; objects such as pipes experience corrosion when buried in soil.

Corrosion potential Potential of a particular soil to cause corrosion of buried iron pipes as a result of soil chemistry.

Cost–benefits analysis A type of site selection in which benefits and costs of a particular project are compared; the most desirable projects are those for which the benefits-to-cost ratio is greater than 1.

Creep A type of downslope movement characterized by slow flowing, sliding, or slipping of soil and other earth materials.

Criteria pollutants The six most common air pollutants: sulfur dioxide, nitrogen oxides, carbon monoxide, ozone and other photochemical oxidants, particulate matter, and lead.

Crust The outermost layer of the solid Earth, embedded in the top of the lithosphere, that varies in thickness from 6 to 7 km below the oceans to as much as 70 km beneath continental mountain ranges.

Crystalline A material with a definite internal structure such that the atoms are in an orderly, repeating arrangement.

Crystallization Processes of crystal formation.

Crystal settling A sinking of previously formed crystals to the bottom of a magma chamber.

Cultural eutrophication Rapid increase in the abundance of plant life, particularly algae, in freshwater or marine environments resulting from input of nutrients from human sources to the water.

Cutoff trench A trench that is excavated across a slope to intercept surface and subsurface waters and provide drainage, thus decreasing the likelihood of a landslide.

Darcy flux The product of the hydraulic conductivity and hydraulic gradient, which has the units of a velocity.

Darcy's law Empirical relationship that states that the volumetric flow rate such as cubic meters per day is a product of hydraulic conductivity, hydraulic gradient, and cross-sectional area of flow; developed by Henry Darcy in 1856.

Debris avalanche A type of mass wasting characterized by a rapid downslope movement of soil and/or other rock debris on steep slopes; may result from saturation after a heavy rainfall or other processes such as volcanic eruptions that cause the failure on the side of a volcano.

Debris flow (mudflow/lahar) Rapid downslope movement of Earth material often involving saturated, unconsolidated material that has become unstable because of torrential rainfall.

Deep-well disposal Method of waste disposal that involves pumping waste into subsurface disposal sites such as fractured or otherwise porous rocks.

Deflation The process of removing loose sand or dust by the action of wind.

Delta A deposit of sediments that forms where a river flows into a lake or the ocean and commonly has the shape of the Greek letter delta (Δ); actual shape may be highly variable depending on the relative importance of river processes and coastal processes. It is a landform of very low relief with distributary channels that spread out the flow through a system of channels.

Dendrochronology Study of tree rings to establish a chronology.

Desalination Engineering processes and technology that reduce salinity of water to such a level that it may be consumed by people or used in agriculture.

Desert A difficult term to define scientifically, but classification is mostly based on climatic data, type of vegetation, type of soil, and the general look of a landscape, commonly in an arid or semiarid region.

Desertification Conversion of land from a more productive state to one more nearly resembling a desert.

Detrital Mineral and rock fragments derived from preexisting rocks.

Diagenesis Physical and chemical processes and changes in sediments following deposition which produce sedimentary rocks.

Diamond Very hard mineral composed of the element carbon.

Dike Generally, a relatively long, narrow igneous intrusion.

Dioxin An organic compound composed of oxygen, hydrogen, carbon, and chlorine; a by-product resulting from chemical reactions in the production of other chemicals such as herbicides; may be extremely toxic to mammals and damage ecosystems.

Directivity With respect to earthquake hazards, refers to the fact that during some moderate to large earthquakes the rupture of the fault is in a particular direction and the intensity of seismic shaking is greater in that direction.

Disaster preparedness With respect to natural hazards, refers to the actions of individuals, families, cities, states, or entire nations taken before a hazardous event to plan for that event and to minimize losses.

Discharge The quantity of water flowing past a particular point on a stream, usually measured in cubic feet per second (cfs) or cubic meters per second (cms).

Disease From an environmental viewpoint, disease may be considered as an imbalance that results in part from a poor adjustment between an individual and his or her environment.

Disseminated mineral deposit Mineral deposit in which ore is scattered throughout the rocks; examples are diamonds in kimberlite and many copper deposits.

Dissolved load That part of the load that a river carries that results from chemical dissolution of rocks in the drainage basin.

Disturbance From an ecological viewpoint, refers to an event that disrupts a system; examples include wildfires or hurricanes that cause considerable environmental change.

Divergence of wave normals With respect to coastal processes, refers to areas where wave heights and erosive capability of waves are relatively low compared to other locations; often found in bays and other areas where sand is more likely to be deposited on beaches.

Divergent boundary Boundary between lithospheric plates characterized by production of new lithosphere; found along oceanic ridges.

Dose dependency Refers to the effects of a certain trace element on a particular organism being dependent on the dose or concentration of the element.

Dose-response curves A graph showing the relationship between response and dose of a particular trace element on a particular population of organisms.

Doubling time The time necessary for a quantity of whatever is being measured to double.

Downstream floods Floods produced by storms of long duration that saturate the soil and produce increased runoff over a relatively wide area. Often are of regional extent.

Drainage basin Area that contributes surface water to a particular steam network.

Drainage control Refers to the development of surface and subsurface drains to increase the stability of a slope.

Drainage net System of stream channels that coalesce to form a stream system.

Dredge spoils Solid material, such as sand, silt, clay, or rock deposited from industrial and municipal discharges, that is removed from the bottom of a water body to improve navigation.

Driving forces Those forces that tend to make Earth material slide.

Ductile Material that ruptures after elastic and plastic deformation.

Dynamic equilibrium A steady state of a system that with negative feedback will return to a quasi-equilibrium state following disturbance.

E soil horizon A light-colored horizon underlying the *A* horizon that is leached of iron-bearing compounds.

E-waste Waste from electronic devices such as computers, cell phones, iPods, and the like.

E-zone With respect to coastal erosion, refers to the zone that is expected to erode within a particular time period.

Earth flow Type of mass wasting or landslide characterized by water-saturated Earth materials moving downslope, often with an upper slumping and lower flow type of deformation.

Earthquake Natural shaking or vibrating of Earth in response to the breaking of rocks along faults. The earthquake zones of Earth generally are correlated with lithospheric plate boundaries.

Earthquake cycle A hypothesis to explain periodic occurrence of earthquakes based on drop in elastic strain after an earthquake and reaccumulation of strain before the next event.

Earth's energy balance Refers to the balance between incoming solar radiation and outgoing radiation from Earth; involves consideration of changes in the energy's form as it moves through the atmosphere, oceans, and land, as well as living things, before being radiated back into space.

Earth system science The study of Earth as a system.

Ease of excavation (soil) Measure of how easily a soil may be removed by human operators and equipment.

Ecological restoration Application of ecology to restore ecosystems such as rivers, wetlands, beaches, or sand dunes that have been degraded. Also the restoration of land following activities such as mining and timber harvesting.

Ecology Branch of biology that treats relationships between organisms and their environments.

Economic geology Application of geology to locating and evaluating mineral materials.

Ecosystem A community of organisms and its nonliving environment in which chemical elements cycle and energy flows.

Efficiency With respect to energy resources, refers to designing and using equipment that yields more power from a given amount of energy, resulting in wasting less of the energy to the environment as heat.

Effluent Any material that flows outward from something; examples include wastewater from hydroelectric plants and water discharged into streams from waste-disposal sites.

Effluent stream Stream in which flow is maintained during the dry season by groundwater seepage into the channel.

Elastic deformation Type of deformation in which material returns to its original shape after the stress is removed.

Element A chemical substance composed of identical atoms that cannot be separated by ordinary chemical means into different substances.

El Niño An event during which trade winds weaken or even reverse and the eastern equatorial Pacific Ocean becomes anomalously warm; the westward moving equatorial current weakens or reverses.

Emergency planning Planning for projects after catastrophic events such as hurricanes, floods, or other events.

Engineering geology Application of geologic information to engineering problems.

Environment Both physical and cultural surroundings that surround an individual or a community; also sometimes denotes a certain set of circumstances surrounding a particular occurrence, for example, environments of deposition.

Environmental audit The study of past land use at a particular site, often determined from analyzing old maps and aerial photographs but may involve drilling and sampling of soil and groundwater.

Environmental crisis Refers to the hypothesis that environmental degradation has reached a crisis point as a result of human use of the environment.

Environmental geology Application of geologic information to environmental problems.

Environmental geology map A map that combines geologic and hydrologic data expressed in nontechnical terms to facilitate general understanding by a large audience.

Environmental impact statement (EIS) A written statement that assesses and explores the possible impacts of a particular project that may affect the human environment; required by the National Environmental Policy Act of 1969.

Environmental law A field of law concerning the conservation and use of natural resources and the control of pollution.

Environmental resource unit (ERU) A portion of the environment with a similar set of physical and biological characteristics, a supposedly natural division characterized by specific patterns or assemblages of structural components (such as rocks, soils, and vegetation) and natural processes (such as erosion, runoff, and soil processes).

Environmental unity A principle of environmental studies that states that everything is connected to everything else.

Ephemeral Temporary or very short lived; characteristic of beaches, lakes, and some stream channels that change rapidly (geologically).

Epicenter The point on the surface of Earth directly above the hypocenter (area of first motion) of an earthquake.

Erodibility (soil) Measure of how easily a soil may erode.

Evaporite deposits Sediments deposited from water as a result of extensive evaporation of seawater or lake water; dissolved materials left behind following evaporation.

Expansive soil With respect to engineering properties of soils, refers to soils that, upon wetting and drying, will alternately expand and contract, causing problems for foundations of buildings and other structures.

Exponential growth A type of compound growth in which a total amount or number increases at a certain percentage each year, and each year's rate of growth is added to the total from the previous year; characteristically stated in terms of a particular doubling time, that is, the time in years it will take the original number to double; commonly used in reference to population growth.

Extrusive igneous rocks Igneous rock that forms when magma reaches the surface of Earth; a volcanic rock.

Facies With respect to sediments, in a sedimentary rock refers to characteristics that most often reflect the process or conditions of original deposition of the sediment with respect to its composition and grain size.

Factor of safety (also called safety factor) For slope stability defined as the ratio of resisting to driving forces.

Falling With respect to mass wasting and landslides, refers to Earth materials such as rocks that fall from steep slopes.

Fault A fracture or fracture system that has experienced movement along opposite sides of the fracture.

Fault gouge A clay zone formed by pulverized rock during an earthquake, which may create a groundwater barrier.

Fault scarp A steep slope that is formed by a fault rupture at the surface of Earth.

Fault segmentation A concept recognizing that faults may be divided into specific segments depending upon their geometry, structure, and earthquake history.

Fecal coliform bacteria A type of bacteria commonly found in the gut of humans and other animals; usually harmless, but can cause some diseases; commonly used as a measure of biological pollution.

Feedback The response of a system by which output from the system serves as input back into the system, causing change.

Feldspar The most abundant family of minerals in the crust of Earth; silicates of calcium, sodium, and potassium.

Ferromagnesian mineral Silicate minerals containing iron and magnesium, characteristically dark.

Fertile material Material such as uranium-238, which is not naturally fissionable but upon bombardment by neutrons is converted to plutonium-239, which is fissionable.

Fetch The distance in which wind blows over a body of water; one of the factors significant in determining the height of windblown waves.

Fission The splitting of an atom into smaller fragments with the release of energy.

Flash flood A type of upstream flood in which the floodwaters rise quickly.

Flashy discharge Stream flow characterized by a short lag time or response time between when precipitation falls and peak discharge of a stream occurs.

Flood-hazard mapping The mapping of the floodplain and levels of water inundation from floods of a particular magnitude for the purpose of delineating the flood hazard.

Flooding From an environmental perspective, refers to overbank flow of rivers causing potential damage to human facilities; as a natural process, refers to overbank flows that may lead to the construction of floodplains adjacent to the river channel.

Floodplain Flat topography adjacent to a stream in a river valley, produced by the combination of overbank flow and lateral migration of meander bends.

Floodplain regulation A process of delineating floodplains and regulating land uses on them.

Floodplain zoning Designating appropriate land uses in areas where flooding has occurred or is likely to occur in the future.

Flood-proofing With respect to flood hazards, refers to the construction and modification of buildings and other structures so that they are not inundated by floodwaters.

Flowage (flow) With respect to mass wasting and landsliding, refers to downslope movement of earth materials that deform as a fluid.

Fluid potential The primary driving force of moving water both in the surface and subsurface environments; in general, refers to the elevation or height of a mass of water above a particular reference.

Fluorine Important trace element, essential for nutrition.

Fluvial Concerning or pertaining to rivers.

Fly ash Very fine particles (ash) resulting from the burning of fuels such as coal.

Focus The point or location in Earth where earthquake energy is first released; during an earthquake event, seismic energy radiates out from the focus.

Fold Bend that develops in stratified rocks because of tectonic forces.

Foliation Property of metamorphic rock characterized by parallel alignment of the platy or elongated mineral grains; environmentally important because it can affect the strength and hydrologic properties of rock.

Forcing With respect to global warming, a factor or variable that contributes to global warming, as, for example, anthropogenic forcing from burning fossil fuels.

Forecast With respect to natural hazards, refers to an announcement that states that a particular event such as a flood is likely to occur at a particular time, often with some probability as to how likely the event is.

Foreshocks Small to moderate earthquakes occurring before the main event.

Formation Any rock unit that can be mapped.

Fossil The remains or evidence of past life, including bones, shells, impressions, and trails, preserved naturally in the geologic record.

Fossil fuels Fuels such as coal, oil, and gas formed by the alteration and decomposition of plants and animals from a previous geologic time.

Fracture zone A fracture system that may or may not be active and may or may not have an alteration zone along the fracture planes; environmentally important because fracture zones greatly affect the strength of rocks.

Frequency The number of waves passing a point of reference per second (units are cycles per second or hertz, Hz); the inverse of the wave period.

Friction With respect to deformation of Earth materials, for example, faulting or landsliding, refers to forces that resist motion, usually defined along a plane, such as a fracture or slip plane of a landslide.

Fuel cell A device that produces electricity directly from a chemical reaction; commonly uses hydrogen as a fuel to which an oxidant is supplied.

Fugitive sources Stationary air pollution sources that generate pollutants from open spaces exposed to wind processes.

Fumarole A natural vent from which fumes or vapors are emitted, such as the geysers and hot springs characteristic of volcanic areas.

Fusion, nuclear Combining of light elements to form heavy elements with the release of energy.

Gabbro A dark, coarse-grained igneous rock with minerals such as calcium-rich feldspar, olivine, and pyroxene.

Gaging station Location at a stream channel where discharge of water is measured.

Gaia hypothesis A series of hypotheses that explain how Earth as a system may operate with respect to life. Metaphorically, Earth is viewed as a giant organism consisting of various interactive systems with distinct feedback and thresholds that result in producing an environment beneficial to the many life forms on Earth. Furthermore, life is an important ingredient in producing that environment.

Gamma radiation Type of nuclear radiation consisting of energetic and penetrating rays similar to X-rays emitted during radioactive decay.

Gasification Method of producing gas from coal.

General Circulation Model (GCM) Group of computer models that focus on climate change using a series of equations, often based on conservation of mass and energy.

Geochemical cycle Migratory paths of elements during geologic changes and processes.

Geochemistry Earth chemistry; the study of the abundance and distribution of chemical elements within soil, rock, and water.

Geochronology Chronology of Earth events from numeric dating methods.

Geographic Information System (GIS) Technology capable of storing, retrieving, transforming, and displaying spatial environmental data.

Geologic cycle A group of interrelated cycles known as the hydrologic, rock, tectonic, and geochemical cycles.

Geologic time Time extending from the beginning of Earth to the present; determined in part from Earth's history as recorded in the rocks and sediments that have been deposited and formed at various times; the geologic time scale is the chronological arrangement of rocks of various ages, generally from the oldest event to the youngest.

Geology The science of Earth, including its structure, composition, and history.

Geomorphology The study of landforms and surface processes.

Geopressured system Type of geothermal energy system resulting from trapping the normal heat flow from Earth by impermeable layers such as shale rock.

Geothermal energy The useful conversion of natural heat from the interior of Earth.

Geothermal gradient The rate of increase of temperature beneath the surface of Earth with depth; the average increase is approximately 25°C per kilometer.

Geyser A particular type of hot spring that ejects hot water and steam above the surface of Earth; perhaps the most famous is Old Faithful in Yellowstone National Park.

Glacial surge A sudden or quick advance of a glacier.

Glacier A landbound mass of moving ice.

Global circulation models Refers to computer models used to predict global change, such as increase in mean temperature, precipitation, or some other climatic variable.

Global dimming Slight cooling caused by human release of air pollution particles that reflect incoming solar radiation back to space.

Global warming (anthropogenic) Refers to the hypothesis that the mean annual temperature of the lower atmosphere is increasing as a result of burning fossil fuels and emitting greenhouse gases into the atmosphere.

Gneiss A coarse-grained, foliated metamorphic rock in which there is banding of light and dark minerals.

Grading of slopes Cut-and-fill activities designed to increase the stability of a slope.

Granite Coarse-grained intrusive igneous rock with minerals such as potassium-rich feldspar, quartz, and mica.

Gravel Unconsolidated, generally rounded fragments of rocks and minerals greater than 2 mm in diameter.

Gravitational water Water that occurs in pore spaces of a soil and is free to drain from the soil mass under the influence of gravity.

Greenhouse effect Trapping of heat in the atmosphere by water vapor, carbon dioxide, methane, and chlorofluorocarbons (CFCs).

Groin A structure designed to protect shorelines and trap sediment in the zone of littoral drift, generally constructed perpendicular to the shoreline.

Groin field With respect to coastal processes, refers to a group of groins.

Groundwater Water found beneath the surface of Earth within the zone of saturation.

Groundwater discharge Refers to the outflow of groundwater, as from a well, spring, or seepage into stream channels.

Groundwater flow Movement of water in the subsurface below the groundwater table.

Groundwater recharge Refers to the process whereby surface waters infiltrate the soil and vadose zone to eventually augment groundwater resources.

Groundwater system With respect to geothermal energy, refers to the use of groundwater resources at normal temperatures to provide energy for heating and cooling.

Groundwater treatment Refers to a variety of physical, chemical, and biological processes utilized to remove pollutants from groundwater.

Grout A mixture of cement and sediment that is sufficiently fluid to be pumped into open fissures or cracks in rocks, thereby increasing the strength of a foundation for an engineering structure.

Growth rate A rate usually measured as a percentage by which something is changing; for example, if you earn 5 percent interest in a bank account per year, then the growth rate is 5 percent per year.

Gypsum An evaporite mineral, $CaSO_4 \cdot 2H_2O$.

Half-life The amount of time necessary for one-half of the atoms of a particular radioactive element to decay.

Halite A common mineral, NaCl (salt).

Hardpan soil horizon Hard, compacted, or cemented soil horizon, most often composed of clay but sometimes cemented with calcium carbonate, iron oxide, or silica; nearly impermeable and often restricts the downward movement of soil water.

Hard path From an environmental energy perspective, refers to use of large centralized power plants; may be coupled with energy conservation and cogeneration.

Hazardous chemicals Chemicals that are harmful, carcinogenic, or otherwise toxic to humans or other living things or ecosystems; most are produced by our industrial/agricultural industries, but some have natural sources as well.

Hazardous waste Waste materials determined to be toxic or otherwise harmful to people and the environment.

Heavy metals With respect to geochemistry and environmental health, refers to metals such as lead, selenium, zinc, and others that may be harmful in small concentrations in the environment.

Hematite An important ore of iron, a mineral (Fe_2O_3).

High-level waste Commercial and military spent nuclear fuel consisting in part of uranium and plutonium that is extremely toxic.

High-value resource Materials such as diamonds, copper, gold, and aluminum; these materials are extracted wherever they are found and transported around the world to numerous markets.

Hot igneous system Type of geothermal energy system in which heat is supplied by the presence of magma.

Hot spot Assumed stationary heat source located below the lithosphere that feeds volcanic processes near Earth's surface.

Hot spring A natural discharge of groundwater at a temperature higher than the human body.

Hot springs and geysers Features at the surface of Earth where hot water and steam are quietly released or may be explosively erupted.

Humus Black organic material in soil.

Hurricane Tropical cyclone characterized by circulating winds of 100 km/hr or greater generated over an area of about 160 km in diameter; known as typhoons in the Pacific Ocean.

Hydraulic conductivity Measure of the ability of a particular material to allow water to move through it; units are length per time, such as meters per day.

Hydraulic gradient With respect to movement of groundwater, refers to the slope of the groundwater surface or the piezometric surface that is important in the movement of groundwater.

Hydraulic head With respect to groundwater movement, refers to the height of the groundwater above a datum such as sea level.

Hydrocarbon Organic compounds consisting of carbon and hydrogen.

Hydroconsolidation Consolidation of Earth materials when wet.

Hydroelectric power *See* Water power.

Hydrofracturing Pumping of water under high pressure into subsurface rocks to fracture the rocks and thereby increase their permeability.

Hydrogen fluoride An extremely toxic gas, dangerous at very small concentrations.

Hydrogen sulfide A toxic gas that is flammable and has the smell of rotten eggs.

Hydrogeology Discipline that studies relationships between groundwater, surface water, and geology.

Hydrograph A graph of the discharge of a stream over time.

Hydrologic cycle Circulation of water from the oceans to the atmosphere and back to the oceans by way of precipitation, evaporation, runoff from streams and rivers, and groundwater flow.

Hydrologic gradient The driving force for both saturated and unsaturated flow of groundwater; quantitatively, it is the slope or rate of change of the hydraulic head, which at the point of measurement is the algebraic sum of the elevation head and pressure head.

Hydrology The study of surface and subsurface water.

Hydrosphere The water environment in and on Earth and in the atmosphere.

Hydrothermal convection system Geothermal energy system characterized by the circulation of hot water; may be dominated by water vapor or hot water.

Hydrothermal ore deposit A mineral deposit derived from hot-water solutions of magmatic origin.

Hygroscopic water Refers to water absorbed and retained on fine-grained soil particles; may be held tenaciously.

Hypocenter The point in Earth where an earthquake originates; also known as the *focus*.

Hypothesis A statement intended to be a possible answer to a scientific question. The best hypothesis may be tested. Often multiple hypotheses are developed to answer a particular question.

Icebergs Large blocks of glacial ice that break off from the front of a glacier, dropping into the ocean by a process called calving; the block of ice, 90 percent of which is below the surface of the water, then moves with the currents of the ocean.

Ice stream A stream of glacial ice within an ice sheet that moves faster than the ice sheet.

Igneous rocks Rocks formed from solidification of magma; extrusive if they crystallize on the surface of Earth, and intrusive if they crystallize beneath the surface.

Impermeable Earth materials that greatly retard or prevent movement of fluids through them.

Impervious cover With respect to urban hydrology, represents the surface of Earth that is covered with concrete, roofs, or other structures that impede the infiltration of water into the soil; in general, as urbanization proceeds, the percentage of the land that is under impervious cover increases.

Incineration Reduction of combustible waste to inert residue (ash) by burning at high temperatures.

Indoor air pollution Refers to those pollutants that are concentrated within buildings we live and work in.

Industrial ecology Design of industrial systems to be similar to ecosystems where waste from one part of the system is a resource for another.

Infiltration Movement of surface water into rocks or soil.

Influent stream Stream that is everywhere above the groundwater table and flows in direct response to precipitation; water from the channel moves down to the water table, forming a recharge mound.

Input-output analysis A type of systems analysis in which rates of input and output are calculated and compared.

Instream use Water that is used but not withdrawn from its source; for example, water used to generate hydroelectric power.

Instrumental intensity The intensity of shaking from an earthquake obtained from data recorded from a dense network of high-quality seismographs.

Integrated waste management (IWM) A complex set of management alternatives for waste management, including source reduction, recycling, composting, landfill, and incineration.

Intraplate earthquake Earthquakes that occur in the interior of a lithospheric plate, far away from any plate boundary.

Intrusive igneous rock Igneous rock that forms when magma solidifies below the surface of Earth; a volcanic rock.

Island arc A curved group of volcanic islands associated with a deep oceanic trench and subduction zone (convergent plate boundary).

Isostasy The principle stating that thicker, more buoyant crust is topographically higher than crust that is thinner and denser. Also, with respect to mountains, the weight of rocks of the upper crust is compensated by buoyancy of the mass of deeper crystal rocks; that is, mountains have "roots" of lighter crustal rocks extending down into the denser mantle rocks, like icebergs in the ocean.

Isotopes Atoms of the same element having the same number of protons in the nucleus, but differing number of neutrons.

Itai itai disease Extremely painful disease that attacks bones, causing them to become very brittle so that they break easily; associated with the consumption of or exposure to heavy metals, especially cadmium, in concentrations of a few parts per million in the soil or in food.

Jetty Often constructed in pairs at the mouth of a river or inlet to a lagoon, estuary, or bay, designed to stabilize a channel, control deposition of sediment, and deflect large waves.

Joint A rock fracture along which there has been no displacement. Parallel joints form a joint set.

Juvenile water Water derived from the interior of Earth that has not previously existed as atmospheric or surface water.

K soil horizon A calcium carbonate–rich horizon in which the carbonate often forms laminar layers parallel to the surface; carbonate completely fills the pore spaces between soil particles.

K-T boundary Geologic time boundary between the Cretaceous and Tertiary periods, approximately 65 million years ago.

Karst topography A type of topography characterized by the presence of sinkholes, caverns, and diversion of surface water to subterranean routes.

Kimberlite pipe An igneous intrusive body that may contain diamond crystals disseminated (scattered) throughout the rock.

Lag time The time period between when the main mass of precipitation falls and a peak discharge in a stream occurs. With urbanization, the lag time generally decreases.

Land application Alternative for disposal of certain types of hazardous chemical waste in which the waste is applied to the soil and degraded by natural biological activity in the soil.

Land ethic Ethic that affirms the right of all resources, including plants, animals, and earth materials, to continued existence and, at least in some locations, continued existence in a natural state.

Landslide Specifically, rapid downslope movement of rock and/or soil; also a general term for all types of downslope movement.

Land-use planning Complex process involving development of a land-use plan to include a statement of land-use issues, goals, and objectives; summary of data collection and analysis; land-classification map; and report describing and indicating appropriate development in areas of special environmental concern. An extremely controversial issue.

Lateral blast Type of volcanic eruption characterized by explosive activity that is more or less parallel to the surface of Earth. Lateral blast may occur when catastrophic failure of the side of a volcano occurs.

Laterite Soil formed from intense chemical weathering in tropical or savanna regions.

Lava Molten material produced from a volcanic eruption, or rock that forms from solidification of molten material.

Lava flow Eruption of magma at the surface of Earth that generally flows downslope from volcanic vents.

Lava tube A natural conduit or tunnel through which magma moves from a volcanic event downslope (sometimes many kilometers) to where the magma may again emerge at the surface; after the volcanic eruption, the tubes are often left as open voids and are a type of cave.

Law of cross-cutting relationships Fundamental law of geology that states a rock is younger than any rock it cuts across; application of this law assists in determining the relative ages of rocks.

Law of faunal assemblages Also known as the *law of faunal succession*, this is a general law of the geological sciences that states that the fossils or organisms succeed one another in an order that may be recognized. In other words, the fossil content of sedimentary rocks suggests the rocks' relative ages.

Law of original horizontality A principal law of the geological sciences that states that a sedimentary stratum, at the time it was deposited, was nearly horizontal; this does not mean that individual grains in a stratum are deposited horizontally, but that the sedimentary bed itself is essentially horizontal.

Law of superposition A fundamental law of the geological sciences that states that for any sequence of sedimentary strata that has not been overturned, the youngest rocks are at the top and the oldest at the bottom or base of the sedimentary sequence. Another way of stating it is that for any given strata or sedimentary unit, rocks above are younger and those below are older.

Leachate Noxious liquid material capable of carrying bacteria, produced when surface water or groundwater comes into contact with solid waste.

Leaching Process of dissolving, washing, or draining earth materials by percolation of groundwater or other liquids.

Lead A toxic heavy metal that has been heavily utilized by people for thousands of years, most recently in paints and gasoline.

Levee Natural levees result from overbanked flows of rivers; human-constructed levees are earthen embankments along a river channel to protect land adjacent to the river from flooding.

Lignite A type of low-grade coal.

Limestone A sedimentary rock composed almost entirely of the mineral calcite.

Limonite Rust, hydrated iron oxide.

Liquefaction Transformation of water-saturated granular material from the solid state to a liquid state.

Lithosphere Outer layer of Earth, approximately 100 km thick, that comprises the plates that contain the ocean basins and continents.

Little Ice Age (LIA) Time period of approximately 300 years from the mid 1400s to 1700 where the Earth was cooler than it is today. During the Little Ice Age, glaciers expanded in mountainous regions. Cold, wet years during the Little Ice Age probably contributed to the devastation caused by the Black Plague.

Littoral Pertaining to the nearshore and beach environments.

Littoral cell Segment of coastline that includes an entire cycle of sediment delivery to the coast, longshore littoral transport, and eventual loss of sediment from the nearshore environment.

Loess Deposits of windblown silt.

Longitudinal profile With respect to the study of rivers, refers to the profile of a stream channel that is generally concave and represents a graph of the relationship between elevation and distance downstream from a reference point.

Longshore bar and trough Elongated depression and adjacent ridge of sand roughly parallel to shore produced by wave action.

Longshore current A current of water and moving sediment that develops in the surf zone as the result of waves that strike the land at an angle.

Longshore sediment transport With respect to coastal processes, refers to the transport of sediment in the nearshore environment by wave activity.

Low-level radioactive waste Materials that contain only small amounts of radioactive substances.

Low-value resource Resources such as sand and gravel that have primarily a place value, economically extracted because they are located close to where they are to be used.

Magma A naturally occurring molten rock material, much of which is in a liquid state.

Magma tap Attempt to recover geothermal heat directly from magma; feasibility of such heat extraction is unknown.

Magmatic differentiation Physical and chemical processes that result in different chemical composition and thus mineralogy of igneous rock from a common magma source.

Magnetic reversal Involves the change of Earth's magnetic field between normal polarity and reverse polarity; also sometimes known as *geomagnetic reversal*.

Magnetite A mineral and important ore of iron, Fe_3O_4.

Magnitude-frequency concept The concept that states that the magnitude of an event is inversely proportional to its frequency.

Manganese oxide nodules Nodules of manganese, iron with secondary copper, nickel, and cobalt, which cover vast areas of the deep-ocean floor.

Mantle An internal layer of Earth approximately 3000 km thick composed of rocks that are primarily iron and magnesium-rich silicates. The lower boundary of the mantle is with the core, and the upper boundary is with the crust. The boundary is known as the *Mohorovičić discontinuity* (also called the *Moho*).

Marble Metamorphosed limestone.

Marl Unconsolidated clays, silts, sands, or mixtures of these materials that contain a variable content of calcareous material.

Mass extinction Sudden loss of large numbers of plant and animal species relative to new species being added.

Mass wasting A comprehensive term for any type of downslope movement of earth materials.

Material amplification Refers to the phenomenon that some Earth materials will cause the amplitude of seismic shaking to increase. This is generally associated with soft sediment, such as silt and clay deposits.

Materials management Making better use of materials to reduce the waste we produce.

Maximum credible earthquake The largest earthquake that may reasonably be assumed to occur at a particular area in light of the tectonic environment, historic earthquakes, and paleoseismicity.

Meandering A type of channel pattern characterized by a sinuous channel with a series of gentle bends that migrate back and forth across a floodplain.

Meanders Bends in a stream channel that migrate back and forth across the floodplain, depositing sediment on the inside of the bends, forming point bars, and eroding outsides of bends.

Mediation Process of working toward a solution to a conflict concerning the environment that is advantageous for everyone; a collaborative process that seeks a solution that favors the environment while allowing activities and projects to go forward.

Medieval Warming Period (MWP) Time period of approximately 300 years from A.D. 950 to 1250 when Earth's surface was considerably warmer in western Europe than the normal that we experience today. The MWP in western Europe was a time of flourishing culture and activity, as well as expansion of population.

Meltdown An accident at a nuclear power station in which the reactor core overheats and fuel rods melt.

Metamorphic rock A rock formed from preexisting rock by the effects of heat, pressure, and chemically active fluids beneath Earth's surface. In foliated metamorphic rocks, the mineral grains have a preferential parallel alignment or segregation of minerals; nonfoliated metamorphic rocks have neither.

Meteor Particle from dust to centimeters in size that is destroyed in the Earth's atmosphere (shooting star).

Meteoric water Water derived from the atmosphere.

Meteorite Particle from dust to asteroid size that impacts Earth's surface.

Meteoroid Particle in space from less than 10 m to larger than dust size—may form from breakup of asteroids.

Methane A gas, CH_4; the major constituent of natural gas.

Methane hydrate Icelike compound made of molecules of methane gas that is trapped within cages of frozen water beneath the seafloor at water depths of about 1000 m.

Mica A common rock-forming silicate mineral.

Mid-oceanic ridge A topographic high commonly found in the central part of oceans characterized by seafloor spreading. An example is the Mid-Atlantic Ridge.

Milankovitch cycles Natural cycles of variation of solar radiation that reaches Earth's surface of approximately 20,000, 40,000, and 100,000 years.

Mineral An element or chemical compound that is normally crystalline and is formed as the result of geologic processes.

Mining reclamation *See* Reclamation, mining.

Mining spoils *See* Spoils, mining.

Mitigated negative declaration Environmental statement filed when the initial study of a project suggests that any significant environmental problems that will result from or occur during a project could be modified to mitigate those problems.

Mitigation The identification of actions that will avoid, lessen, or compensate for anticipated adverse environmental impacts.

Mobile sources Moving sources of air pollution such as automobiles.

Modified Mercalli Scale A scale with 12 divisions that subdivide the amount and severity of shaking and damage from an earthquake.

Moho The boundary between the crust and mantle, also known as the *Mohorovičić discontinuity*; distinguished by compositional differences between the rocks of the crust and the mantle.

Moment magnitude The magnitude of an earthquake based on its seismic moment, which is the product of the average amount of slip on the fault that produced the earthquake, the area that actually ruptured, and the shear modulus of the rocks that failed.

Monitoring With respect to waste management, refers to periodic or continuous gathering of samples of soil, vegetation, vadose zone water, and groundwaters in and near waste management facilities, such as landfills or hazardous waste disposal facilities.

Mudflow A mixture of unconsolidated materials and water that flows rapidly downslope or down a channel.

Multiple land use A principle of land use that involves multiple uses at the same time, as, for example, a dam and reservoir designed for flood control, water supply, and recreation.

Myth of superabundance The myth that land and water resources are inexhaustible and management of resources is therefore unnecessary.

National Environmental Policy Act of 1969 (NEPA) Act declaring a national policy that harmony between humans and their physical environment be encouraged; established the Council on Environmental Quality and requirements that an environmental impact statement be completed before major federal actions that significantly affect the quality of the human environment.

Natural gas Sometimes also referred to as *natural energy gas* or *hydrocarbons* that include ethane, propane, butane, and hydrogen.

Natural hazards Refers to processes, such as earthquakes, floods, and volcanic eruptions, that produce a hazard to people and property.

Near Earth object Asteroids that reside and orbit between the Earth and the Sun or have orbits that intersect Earth's orbit.

Negative declaration The filing of a statement that declares that the environment will experience no significant effects from a particular project or plan.

Negative feedback A type of feedback in which the outcome moderates or decreases the process, often leading to a steady-state system or a system in quasi-equilibrium (is self-regulating).

Negotiation With respect to environmental law, refers to processes whereby parties that differ on a particular issue sit down and talk and try to work out an agreement.

Neutron A subatomic particle having no electric charge, found in the nuclei of atoms; crucial in sustaining nuclear fission in a reactor.

Nitrogen oxides (NO_x) Group of gases emitted as a result of burning fossil fuels in automobiles and at power plants; includes compounds such as nitrogen dioxide (NO_2), which is a light yellow-brown to reddish brown gas that is a main pollutant contributing to the development of photochemical smog.

Nonpoint sources Diffused and intermittent sources of air or water pollutants.

Nonrenewable resource A resource cycled so slowly by natural Earth processes that, once used, it will be essentially unavailable during any useful time frame.

Normal fault A generally steep fault with vertical displacement (dip-slip) in which the hanging-wall has moved down relative to the foot-wall.

No-till agriculture Combination of farming practices that does not include plowing of the land.

Nuclear energy Generation of electricity using a nuclear reactor.

Nuclear fusion *See* Fusion, nuclear.

Nuclear reactor Device in which controlled nuclear fission is maintained; the major component of a nuclear power plant.

O soil horizon Soil horizon that contains plant litter and other organic material; found above the *A* soil horizon.

Ocean pollution Pollution of the oceans of the world due to direct or indirect interjection of contaminants to the marine environment, whether deliberate or not; often results from the process of ocean dumping, but there are many sources of ocean pollution.

Offstream use Water removed or diverted from its primary source for a particular use.

Oil When referring to energy resources, may also be known as *petroleum* or *crude oil*; a liquid hydrocarbon generally extracted from wells.

Oil shale Organic-rich shale containing substantial quantities of oil that can be extracted by conventional methods of destructive distillation.

Oil spill The accidental release of oil from a ship transporting oil, an oil pipeline leak, or release of oil from a well during or after drilling.

Open system A type of system in which there is a constant flow of energy and matter across the borders of the system.

Ore Earth material from which a useful commodity can be extracted profitably.

Outcrop A naturally occurring or human-caused exposure of rock at the surface of Earth.

Overburden Earth materials (spoil) that overlie an ore deposit, particularly material overlying or extracted from a surface (strip) mine.

Overland flow Flow of water on the surface of Earth not confined to channels; results because the intensity of precipitation is greater than the rate at which rainwater infiltrates into the ground.

Oxidation Chemical process of combining with oxygen.

Oxides With respect to mineral types, refers to mineral compounds that link oxygen with one or more metallic elements, as for example the mineral hematite (Fe_2O_3).

Ozone Triatomic oxygen (O_3).

Ozone depletion Refers to stratospheric loss of ozone, generally at the South Pole, related to release of chlorofluorocarbons (CFCs) into the atmosphere.

P wave One of the seismic waves produced by an earthquake; the fastest of the seismic waves, it can move through liquid and solid materials.

Paleomagnetic Also known as *paleomagnetism;* refers to the study of magnetism of rocks and the intensity and direction of the magnetic field of Earth in the geologic past.

Particulate matter With respect to air pollutants, refers to small particles of solid or liquid substances that are released into the atmosphere by natural processes and human activities. Examples include smoke, soot, or dust, as well as particles of heavy metals such as copper, lead, and zinc.

Passive method With respect to permafrost, refers to one of the common methods of trying to minimize problems associated with permafrost that involve keeping the ground frozen and not upsetting the natural balance of environmental factors.

Pathogen Any material that can cause disease; for example, microorganisms, including bacteria and fungi.

Peak oil The time when half of all oil on Earth will have been extracted.

Pebble A rock fragment between 4 and 64 mm in diameter.

Ped An aggregate of soil particles; classified by shape as spheroidal, blocky, prismatic, and so on.

Pedology The study of soils.

Pegmatite A coarse-grained igneous rock that may contain rare minerals rich in elements such as lithium, boron, fluorine, uranium, and others.

Perched water table Existence of a water table of relatively limited extent that is found at a higher elevation than the more regional water table.

Percolation test A standard test for determining the rate at which water will infiltrate into the soil; primarily used to determine feasibility of a septic-tank disposal system.

Permafrost Permanently frozen ground.

Permeability A measure of the ability of an Earth material to transmit fluids such as water or oil. *See* Hydraulic conductivity.

Petrology Study of rocks and minerals.

Phenocrysts Large crystals in an igneous rock with a porphyritic texture.

Photochemical smog Usually referred to as LA smog or brown air; forms as a result of interactions between solar radiation and automobile exhaust.

Photovoltaics Type of solar technology that converts sunlight directly to electricity.

Physiographic determinism Site selection based on the philosophy of designing with nature.

Physiographic province Region characterized by a particular assemblage of landforms, climate, and geomorphic history.

Placer deposit Ore deposit found in material transported and deposited by such agents as running water, ice, or wind; for example, gold and diamonds found in stream deposits.

Plastic deformation Deformation that involves a permanent change of shape without rupture.

Plate tectonics A model of global tectonics that suggests that the outer layer of Earth, known as the *lithosphere*, is composed of several large plates that move relative to one another; continents and ocean basins are passive riders on these plates.

Plume With respect to groundwater and groundwater pollution, refers to an often elongated three-dimensional mass of polluted or contaminant groundwater that is generally moving away from a contaminant source.

Plunging breaker A type of wave or breaker from a storm that strikes a shoreline with a relatively steep beach profile; tends to be associated with beach erosion.

Pluton Any of several types of igneous intrusions that are variable in size, including dikes and sills; generally, batholiths are composed of a number of plutons.

Plutonium-239 A radioactive element produced in a nuclear reactor; has a half-life of approximately 24,000 years.

PM-2.5 With respect to air pollution, refers to particulate matter less than 2.5 millionths of a meter in size.

PM-10 With respect to air pollution, refers to particulate matter less than 10 millionths of a meter in size.

Point bar Accumulation of sand and other sediments on the inside of meander bends in stream channels.

Point sources Usually discrete and confined sources of air or water pollutants such as pipes that enter into a stream or river or stacks emitting waste from factories or other facilities into the atmosphere.

Pollutant Any substance in the environment that in excess is known to be harmful to people or other desirable living organisms.

Pollution Any substance, biological or chemical, of which an identified excess is known to be detrimental to desirable living organisms.

Pool Common bed form produced by scour in meandering and straight stream channels with relatively low channel slope; characterized at low flow by slow-moving, deep water; generally, but not exclusively, found on the outside of meander bends.

Porosity The percentage of void (empty space) in earth material such as soil or rock.

Porphyritic Refers to a specific texture of igneous rocks characterized by relatively few, often earlier-formed, coarse-grained crystals (phenocrysts) surrounded by a mass of fine-grained, later-formed crystals.

Positive feedback A type of system in which the output amplifies the input, leading to what some call a vicious cycle. Another way of looking at positive feedback is the more you have, the more you get.

Potable water Water that may be safe to drink.

Precautionary principle An environmental planning tool that advocates taking cost-effective, proactive steps to eliminate or reduce the consequences of an environmental problem even if the science is not completely worked out. In simple words, better safe than sorry.

Precursor events With respect to natural hazards, refers to physical, chemical, or biological events that occur before an event such as a flood, earthquake, or volcanic eruption.

Prediction A statement that an event with specified magnitude, such as a tsunami or flood, will happen during a particular time interval. Contrast with forecast, which provides a percent chance of something happening.

Primary pollutants With respect to air pollution, refers to those pollutants emitted directly into the atmosphere, including particulates, sulfur oxides, carbon monoxide, nitrogen oxides, and hydrocarbons.

Primary treatment With respect to a wastewater treatment plant, includes screening and removal of grit and sedimentation of larger particles from the waste stream.

Pyrite Iron sulfide, a mineral commonly known as *fool's gold;* environmentally important because, in contact with oxygen-rich water, it produces a weak acid that can pollute water or dissolve other minerals.

Pyroclastic activity Type of volcanic activity characterized by eruptive or explosive activity in which all types of volcanic debris, from ash to very large particles, are physically blown from a volcanic vent.

Pyroclastic deposits Refers to particles forcefully ejected from a volcanic vent, explosive in origin, containing volcanic ash particles and those of larger size such as blocks and bombs.

Pyroclastic flow Rapid subaerial flowage of eruptive material consisting of volcanic gases, ash, and other materials that move rapidly down the flank of a volcano; often form as the result of the collapse of an eruption column; may also be known as *ash flows, fiery clouds*, or *nueé ardentes*.

Quartz Silicon oxide, a common rock-forming mineral.

Quartzite Metamorphosed sandstone composed of quartz grains.

Quick clay Type of clay that, when disturbed, such as by seismic shaking, may experience spontaneous liquefaction and lose all shear strength.

R soil horizon Consolidated bedrock that underlies the soil.

Radioactive waste Type of waste produced in the nuclear fuel cycle, generally classified as high level or low level.

Radioactive waste management Refers to waste-management policies and procedures related to radioactive waste.

Radioisotope A form of a chemical element that spontaneously undergoes radioactive decay, changing from one isotope to another and emitting radiation in the process.

Radon A colorless, radioactive, gaseous element.

Rapid drawdown Rapid decrease in the elevation of the water table at a particular location due to a variety of processes, including receding flood waters or lowering of the water in a reservoir.

Reclaimed water Water that has been treated by wastewater handling facilities and may be used for other purposes on discharge, such as irrigation of golf courses or croplands.

Reclamation, mining Restoring land used for mining to other useful purposes, such as agriculture or recreation, after mining operations are concluded.

Record of decision A concise statement by an agency planning a proposed project as to which alternatives were considered and, specifically, which alternatives are environmentally preferable; becoming an important part of environmental impact work.

Recurrence interval The time between events, such as floods or earthquakes or other natural processes. Often we are interested in the average recurrence interval, which is determined by finding the mean of a series of recurrence intervals between events.

Recycling The reuse of resources reclaimed from waste.

Reduce, recycle, and reuse The three R's of integrated waste management that describe the objective of reducing the amount of waste that must be disposed of in landfills or other facilities.

Refraction With respect to coastal processes, refers to the bending of surface waves as they enter shallow water and "feel bottom"; that part of a wave that first "feels bottom" and slows down, bending the wave.

Regional metamorphism Wide-scale metamorphism of deeply buried rocks by regional stress accompanied by elevated temperatures and pressures.

Relative profile development Refers to soils that may be weakly, moderately, or strongly developed, depending on specific soil properties.

Renewable energy Energy sources that are replenished quickly enough to maintain a constant supply if they are not overused; examples include solar energy, water power, and wind energy.

Renewable resource A resource such as timber, water, or air that is naturally recycled or recycled by human-induced processes within a useful time frame.

Reserves Known and identified deposits of earth materials from which useful materials can be extracted profitably with existing technology under present economic and legal conditions.

Residual deposits With respect to mineral resources, refers to those deposits that form as a result of the mechanical concentration of a particular mineral, as for example gold nuggets in a stream or decomposition in weathered rocks.

Residual soil Refers to soils that develop on bedrock.

Resisting forces Forces that tend to oppose downslope movement of earth materials.

Resistivity A measure of an earth material's ability to retard the flow of electricity; the opposite of conductivity.

Resources Includes reserves plus other deposits of useful earth materials that may eventually become available.

Retaining wall A structure constructed to buttress the toe area of a slope to minimize the likelihood of a landslide.

Reverse fault A fault with vertical displacement in which the hanging-wall has moved up relative to the foot-wall; a low-angle reverse fault is called a thrust fault.

Rhyolite A type of volcanic rock consisting of feldspar, ferromagnesian, and quartz minerals with a relatively high silica content of about 70 percent; associated with volcanic events that may be very explosive.

Richter magnitude A measure of the amount of energy released by an earthquake, determined by converting the largest amplitude of the shear wave to a logarithmic scale in which, for example, 2 indicates the smallest earthquake that can be felt and 8.5 indicates a devastating earthquake.

Ridge push A gravitational push similar to a gigantic landslide responsible for pushing the plates apart at divergent plate boundaries.

Riffle A section of stream channel characterized at low flow by fast, shallow flow; generally contains relatively coarse bed load particles.

Riparian doctrine Part of our prevailing water law restricted for the most part to owners of land adjoining a stream or body of standing water.

Riparian rights, water law Right of the landowner to make reasonable use of water on his or her land, provided the water is returned to the natural stream channel before it leaves the property; the property owner has the right to receive the full flow of the stream undiminished in quantity and quality.

Rip current A seaward flow of water in a confined narrow zone from a beach to beyond the breaker zone.

Rippable excavation Type of excavation that requires breaking up soil before it can be removed.

Riprap Layer or assemblage of broken stones placed to protect an embankment against erosion by running water or breaking waves.

Risk From an environmental viewpoint, risk may be considered as the product of the probability of an event times the consequences.

Risk assessment In terms of toxicology, the process of determining potential adverse environmental health effects following exposure to a particular toxic material.

Risk management With respect to toxicology, the process of integrating risk assessment with legal, social, political, economic, and technical issues to develop a plan of action for a particular toxin.

Riverine environment Land area adjacent to and influenced by a river.

Rock Geologic: An aggregate of a mineral or minerals. Engineering: Any earth material that must be blasted to be removed.

Rock cycle Group of processes that produce igneous, metamorphic, and sedimentary rocks.

Rock salt Rock composed of the mineral halite.

Rock texture *See* Texture, rock.

Rotational landslide Type of landslide that develops in homogeneous material; movement is likely to be rotational along a potential slide plane.

Runoff Water moving over the surface of Earth as overland flow on slopes or stream flow; that part of the hydrologic cycle represented by precipitation or snowmelt that results in stream flow.

S wave Secondary wave, one of the waves produced by earthquakes.

Safety factor (SF) With respect to landsliding, refers to the ratio of resisting to driving forces; a safety factor of greater than 1 suggests a slope is stable.

Saline Salty; characterized by high salinity.

Salinity A measure of the total amount of dissolved solids in water.

Salt dome A structure produced by upward movement of a mass of salt; frequently associated with oil and gas deposits on the flanks of a dome.

Saltwater intrusion Process whereby fresh groundwater may be displaced by saltwater, often as a result of pumping of groundwater resources.

Sand Grains of sediment with a size between 1/16 and 2 mm in diameter; often, sediment composed of quartz particles of this size.

Sand dune Ridge or hill of sand formed by wind action.

Sandstone Detrital sedimentary rock composed of sand grains that have been cemented together.

Sanitary landfill Method of solid-waste disposal that does not produce a public health problem or nuisance; confines and compresses waste and covers it at the end of each day with a layer of compacted, relatively impermeable material, such as clay.

Saturated flow A type of subsurface or groundwater flow in which all the pore spaces are filled with water.

Scarp Steep slope or cliff commonly associated with landslides or earthquakes.

Scenic resources The visual portion of an aesthetic experience; scenery is now recognized as a natural resource with varying values.

Schist Coarse-grained metamorphic rock characterized by foliated texture of the platy or elongated mineral grains.

Schistosomiasis Snail fever, a debilitating and sometimes fatal tropical disease.

Scientific method The method by which scientists work, starting with the asking of a question concerning a particular problem, followed by development and testing of hypotheses.

Scoping Process of identifying important environmental issues that require detailed evaluation early in the planning of a proposed project; an important part of environmental impact analysis.

Scrubbing Process of removing sulfur dioxide from gases emitted from burning coal in power plants producing electricity.

Sea cliff Steep (commonly near-vertical) bluff adjacent to and adjoining a beach or coastal environment; produced by a combination of erosional processes including wave activity and subaerial processes such as weathering, landsliding, and runoff of surface water from the land.

Seafloor spreading The plate tectonics concept that new crust is continuously added to the edges of lithospheric plates at divergent plate boundaries as a result of upwelling of magma along mid-oceanic ridges.

Seawall Engineering structure constructed at the water's edge to minimize coastal erosion by wave activity.

Secondary enrichment Weathering process of sulfide ore deposits that may concentrate the desired minerals.

Secondary pollutants With respect to air pollution, refers to pollutants produced when primary pollutants react with normal atmospheric compounds; an example is ozone, which forms through reactions between primary pollutants, sunlight, and natural atmospheric gases.

Secondary treatment With respect to wastewater treatment, includes aerobic and anaerobic digestion of waste in the wastewater stream, primarily by bacterial breakdown; final stage is disinfection of treated water, usually with chlorine.

Secure landfill Type of landfill designed to contain and dispose of hazardous chemical waste; many of these facilities have been shut down because containment of the hazardous waste has been impossible to maintain.

Sedimentary environment Environments conducive to the deposition of sediments including lakes, floodplains, sand dunes, and glacial deposits.

Sedimentary rock A rock formed when sediments are transported, deposited, and then lithified by natural cement, compression, or other mechanism; detrital sedimentary rock is formed from broken parts of previously existing rock; chemical sedimentary rock is formed by chemical or biochemical processes removing material carried in chemical solution.

Sedimentology Study of environments of deposition of sediments.

Sediment pollution Pollution of some part of the environment either on land or in a body of water by sediment that has been transported into that environment by wind or water; an example is turbidity of a water supply (muddy water).

Sediment yield Volume or mass of sediment per unit time produced from a particular area.

Seismic Refers to vibrations in Earth produced by earthquakes.

Seismic gaps Areas along active fault zones that are capable of producing large earthquakes but have not produced one recently.

Seismic risk map Map that depicts the seismic risk of a particular area or region; often based on past earthquake activity or on the probability of a specified intensity of a shaking occurring over a specified period of time.

Seismograph Instrument that records earthquakes.

Seismology The study of earthquakes as well as the structure of Earth through the evaluation of both natural and artificially generated seismic waves.

Selenium Important nonmetallic trace element with an atomic number of 34.

Semiarid Those lands characterized with an annual precipitation between 25 and 50 cm/yr.

Sensitivity (soil) Measure of loss of soil strength due to disturbances such as human excavation and remolding.

Septic tank Tank that receives and temporarily holds solid and liquid waste. Anaerobic bacterial activity breaks down the waste, solid wastes are separated out, and liquid waste from the tank overflows into a drainage system.

Sequential land use Development of land previously used as a site for the burial of waste; the specific reuse must be carefully selected.

Serpentine A family of ferromagnesian minerals; environmentally important because they form very weak rocks.

Sewage sludge Solid material that remains after municipal wastewater treatment.

Shake map Map showing pattern and extent of seismic shaking from an earthquake.

Shale Sedimentary rock composed of silt- and clay-sized particles; the most common sedimentary rock.

Shield volcano A broad, convex volcano built up by successive lava flows; the largest of the volcanoes.

Shrink-swell potential (soil) Measure of a soil's tendency to increase and decrease in volume as water content changes.

Silicate minerals The most important group of rock-forming minerals.

Sill A generally planar, tabular igneous intrusion.

Silt Sediment between 1/16 mm and 1/256 mm in diameter.

Sinkhole Surface depression formed by solution of limestone or collapse over a subterranean void such as a cave.

Sinuous channel Type of stream channel (not braided).

Site selection A method of environmental analysis, the purpose of which is to select a site or series of sites for a particular activity.

Slab pull The plate tectonics concept that dictates that as a plate moves farther from a ridge access, it cools and gradually becomes more dense than the asthenosphere beneath it. At the same time, at a subduction zone the heavy plate falls through the lighter mantle and the weight of the descending slab pulls the entire plate.

Slate A fine-grained, foliated metamorphic rock.

Sliding With respect to mass wasting and landsliding, refers to the deformation or downslope movement of a nearly intact block of earth materials along a slip plain.

Slip plane Refers to inclined features such as rock fractures and bedding planes along which landsliding occurs.

Slip rate Long-term rate of slip (displacement) along a fault; usually measured in millimeters or centimeters per year.

Slow earthquake Earthquake produced by fault rupture that can take days to months to complete.

Slump Type of landslide characterized by downward slip of a mass of rock, generally along a curved slide plane.

Smog A general term to refer to visible air pollution, probably first coined in the early part of the twentieth century as a combination of smoke and fog.

Snow avalanche Rapid downslope movement of snow, ice, and rock.

Soft path With respect to energy resources, refers to development of an energy policy that involves alternatives that are renewable, flexible, decentralized, and (to some people) more benign from an environmental viewpoint than the hard path.

Soil Soil science: Earth material so modified by biological, chemical, and physical processes that the material will support rooted plants. Engineering: Earth material that can be removed without blasting.

Soil chronosequence A series of soils arranged in terms of relative soil profile development from youngest to oldest.

Soil fertility Capacity of a soil to supply nutrients (such as nitrogen, phosphorus, and potassium) needed for plant growth when other factors are favorable.

Soil horizons Layers in soil (*A, B, C*, etc.) that differ from one another in chemical, physical, and biological properties.

Soil profile Weathering of earth materials that, along with biological activity and time, produces a soil that contains several horizons distinct from the parent material from which the soil formed.

Soil sensitivity A relative estimate of a soil's ability to maintain its original strength when disturbed and remolded; soils that keep only a portion of their original strength are said to be sensitive.

Soil slip A type of mass wasting event that generally is narrow relative to width and is linear in form; develops during precipitation events on steep slopes; in California, shallow soil slips are commonly referred to as *mud slides*.

Soil strength The shear strength of a soil in terms of a soil's cohesive and frictional forces.

Soil survey A survey consisting of a detailed soil map and descriptions of soils and land-use limitations; usually prepared in cooperation with local government.

Soil taxonomy With respect to soil science, refers to a method of classifying soils developed by the U.S. Department of Agriculture.

Soil texture Refers to the relative proportions of sand-, silt-, and clay-sized particles in a soil.

Solar collector Any of a variety of active and passive devices that collect solar energy; the most common is the flat-plate collector used to heat water.

Solar energy Energy that is collected from the Sun.

Solid waste Material such as refuse, garbage, and trash.

Specific risk The product of the elements at risk, the probability that a specific event will occur, and the vulnerability defined as the proportion of elements at risk.

Spilling breaker A type of wave associated with a shoreline of relatively low slope; spilling breakers tend to be associated with deposition of sand on a beach.

Spoils, mining Banks or piles that are accumulations of overburden removed during mining processes and discarded on the surface.

Spreading center Synonymous with mid-oceanic ridges where new crust is continuously added to the edges of lithospheric plates.

Spring With respect to groundwater processes, refers to the natural discharge of groundwater where the groundwater system intersects the surface of Earth.

Stationary sources With respect to air pollutants, refers to those sources that are relatively fixed in location.

Steady-state system A system in which the input is approximately equal to the output, so a rough equilibrium is established.

Storm surge Wind-driven oceanic waves, usually accompanying a hurricane.

Strain Change in shape or size of a material as a result of applied stress.

Stream power The product of the discharge of a river and its energy slope.

Strength (soil) Ability of a soil to resist deformation; results from cohesive and frictional forces in the soil.

Stress Force per unit area; may be compressive, tensile, or shear.

Strike-slip A fault across which displacement is predominantly horizontal.

Strip mining A method of surface mining.

Subduction Process in which one lithospheric plate descends beneath another.

Subduction zone Convergence of tectonic plates where one plate dives beneath another and is consumed in the mantle.

Submarine trench A relatively narrow, long (often several thousand km), deep (often several km) depression on the ocean floor that forms as a result of convergence of two tectonic plates with subduction of one.

Subsidence Sinking, settling, or other lowering of parts of the crust of Earth.

Subsurface water All of the waters within the lithosphere.

Sulfur dioxide (SO_2) Colorless and odorless gas whose anthropogenic component in the atmosphere results primarily from the burning of fossil fuels.

Sulfurous smog Sometimes referred to as *London-type smog* or *gray air,* produced primarily by burning coal or oil at large power plants where sulfur oxides and particulates produced by the burning produce a concentrated smog.

Supershear Propagation of rupture during an earthquake that is faster than the velocity of shear-waves or surface waves produced by the rupture. The increased shear and shock may significantly increase the damage from a large earthquake.

Surface impoundment Excavated or natural topographic depressions used to hold hazardous liquid waste. Although impoundments are often lined, they have been criticized because they are especially prone to seepage and pollution of soil and groundwaters.

Surface water Waters above the solid surface of Earth.

Surface wave One type of wave produced by earthquakes; generally cause most of the damage to structures on the surface of Earth.

Surf zone That part of the beach and nearshore environment characterized by borelike waves of translation after waves break.

Suspended load Sediment in a stream or river carried off the bottom by the fluid.

Sustainability A difficult term to define but generally refers to development or use of resources in such a way that future generations will have a fair share of Earth's resources and inherit a quality environment. In other words, sustainability refers to types of development that are economically viable, do not damage the environment, and are socially just.

Sustainable energy policy Development of energy policy that finds useful sources of energy that do not have adverse environmental effects or minimizes those effects in such a way that future generations will have access to energy resources and a quality environment.

Sustainable global economy A global economic development that will not harm the environment, will provide for future generations, and is socially just.

Swash zone That part of the coastal environment where waves run up on the beach face and then back again into the ocean where the land meets the water; the runup or wave swash covers part of the beach with shallow water and then the backwash exposes it again.

Swell With respect to coastal processes, refers to the sorting out of waves by period from a storm into groups of waves having more or less uniform heights and lengths, allowing groups of waves to move long distances from storms to coastal areas with relatively little loss of energy.

Syncline Fold in which younger rocks are found in the core of the fold; rocks in the limbs of the fold dip inward toward a common axis.

System Any part of the universe that is isolated in thought or in fact for the purpose of studying or observing changes that occur under various imposed conditions.

Tar sand Naturally occurring sand, sandstone, or limestone that contains an extremely viscous petroleum.

Tectonic Referring to rock deformation.

Tectonic creep Slow, more or less continuous movement along a fault.

Tectonic cycle Part of the geologic cycle; at the global scale, it is the cycle of plate tectonics that produces ocean basins and mountain ranges.

Tephra Any material ejected and physically blown out of a volcano; mostly ash.

Texture, rock The size, shape, and arrangement of mineral grains in rocks.

Theory A strong scientific statement. A hypothesis may become a theory after it has been tested many times and has not been rejected.

Thermal pollution With respect to water pollution, refers to water of elevated temperature, often from the disposal of water used to cool industrial processes or to produce electricity into a body of water such as a lake, river, or ocean.

Threshold A point of change where something happens; for example, a stream bank may erode when the water has sufficient force to dislodge particles; the point at which the erosion starts is the threshold.

Throughflow Downslope shallow subsurface flow of water above the groundwater table.

Thrust fault A low-angle reverse fault.

Tidal energy Electricity generated by tidal power.

Tidal flood A type of flood that occurs in estuaries or coastal rivers as the result of interactions between high tides and storm waves.

Tidal power With respect to energy resources, refers to the useful conversion of tidal currents to produce electrical power.

Till Unstratified, heterogeneous material deposited directly by glacial ice.

Total load With respect to stream processes, refers to the sum of the dissolved, suspended, and bed load that a stream or river carries.

Toxic Harmful, deadly, or poisonous.

Toxicology The science of the study of toxins and their effects on people and other living organisms and ecosystems; also concerned with relationships between toxic materials and resulting clinical and industrial processes.

Transform boundary Synonymous with transform faults, occurring where edges of two plates slide past one another; most are boundaries within oceanic crust; an example on land is the San Andreas fault in California.

Transform fault Type of fault associated with oceanic ridges; may form a plate boundary, such as the San Andreas fault in California.

Translation (slab) landslide Type of landslide in which movement takes place along a definite fracture plane, such as a weak clay layer or bedding plane.

Transported soil Does not refer to any transport process of a soil but rather reflects that the parent material of a soil is material that has been transported to a particular location, such as alluvium to a floodplain or glacial deposit.

Transuranic waste Nuclear waste composed of human-made radioactive elements heavier than uranium.

Trench With respect to plate tectonics, refers to an elongated depression of the seafloor associated with convergent boundaries and subduction zones; often referred to as submarine trenches, which are the sites of some of the deepest oceanic waters on Earth; often located seaward of the subduction zone.

Triple junction Areas where three tectonic plates and their boundaries join.

Tropical cyclone (typhoon) Severe storm generated from a tropical disturbance; called *typhoons* in most of the Pacific Ocean and *hurricanes* in the Western Hemisphere.

Tsunami Seismic sea wave generated mostly by submarine earthquakes, but also by submarine volcanic eruptions, landslides, or impacts of an asteroid; characteristically has very long wave length and moves rapidly in the open sea; incorrectly referred to as a tidal wave.

Tuff Volcanic ash that is compacted, cemented, or welded together.

Typhoon A tropical cyclone that occurs over the Indian Ocean or western Pacific; the counterpart of a hurricane that occurs in the Atlantic.

Unconfined aquifer Aquifer in which there is no impermeable layer restricting the upper surface of the zone of saturation.

Unconformity A buried surface of erosion representing a time of nondeposition; a gap in the geologic record.

Unified soil classification system Classification of soils, widely used in engineering practice, based on amount of coarse particles, fine particles, or organic material.

Uniformitarianism Concept that the present is the key to the past; that is, we can read the geologic record by studying present processes.

Unsaturated flow Type of groundwater flow that occurs when only a portion of the pores is filled with water.

Urban ore Refers to the fact that in some communities the sewage sludge from waste-disposal facilities contains sufficient metal deposits to be considered an ore.

Vadose zone Zone or layer above the water table in which some water may be suspended or moving in a downward migration toward the water table or laterally toward a discharge point.

Virtual water The amount of water necessary to produce a product, such as rice or, in industry, an automobile.

Volatile organic compound Usually abbreviated as VOC when used to describe water or air pollutants; generally are hydrocarbon compounds such as gasoline, benzene, and propane.

Volcanic ash *See* Ash, volcanic.

Volcanic breccia, agglomerate Large rock fragments mixed with ash and other volcanic materials cemented together.

Volcanic crisis A condition in which a volcanic eruption or prospect of an eruption produces a crisis situation for society.

Volcanic dome Type of volcano characterized by very viscous magma with high silica content; activity is generally explosive.

Wadati-Benioff zone Inclined zone of earthquakes produced as a tectonic plate is subducted.

Warning With respect to natural hazards, the announcement of a possible disaster such as a large earthquake or flood that could occur in the near future.

Wastewater renovation and conservation cycle A process of recycling liquid waste that includes return of treated wastewater to crops or irrigation and continued renovation through recharge of groundwater; the reused part involves pumping out the groundwater for municipal, industrial, or other purposes.

Water budget Analysis of sources, sinks, and storage sites for water in a particular area.

Water conservation Practices taken to use water more efficiently and to reduce withdrawal and consumption of water.

Water cycle *See* Hydrologic cycle.

Water management Practice of managing our water resources.

Water pollution Degradation of water quality as measured by biological, chemical, or physical criteria.

Water power Use of flowing water such as in a reservoir to produce electrical power.

Water quality standards In the United States, refers to Environmental Protection Agency minimum standards for drinking water and water for other uses.

Water table Surface that divides the vadose zone from the zone of saturation; the surface below which all the pore space in rocks is saturated with water.

Watershed Land area that contributes water to a particular stream system. *See* Drainage basin.

Wave climate Statistical characterization on an annual basis of wave height, period, and direction for a particular site.

Wave height Refers to the difference in elevation between the trough and the crest of a wave.

Wave length Refers to the horizontal length between successive crests of waves.

Wave period Refers to the time in seconds for successive wave crests to pass a reference point; the inverse of the frequency of the wave.

Weather What is occurring now or in the very near future (few days) in terms of temperature, pressure, cloudiness, precipitation, and winds. The average of weather over longer periods and regions defines the climate.

Weathering Changes that take place in rocks and minerals at or near the surface of Earth in response to physical, chemical, and biological changes; the physical, chemical, and biological breakdown of rocks and minerals.

Wetlands Landscape features such as swamps, marshes, bogs, or prairie potholes that are frequently or continuously inundated by water.

Wind power Technology (mostly windmills) used to extract electrical energy from the wind.

Zero waste The concept related to waste management that asserts that there is no such thing as waste, but only resources out of place.

Zone of saturation Zone or layer below the water table in which all the pore space of rock or soil is saturated.

References

Chapter 1

1. **Diamond, J.** 2010. Intra-island and inter island comparisons in Diamond, J., and Robinson, J. A. 2010. *Natural Experiments of History,* pp. 120–141. Cambridge, MA: Harvard University Press.
2. **Mongabay.** 2010. Deforestation Figures for Selected Countries. http://rainforests.mongabay.com/deforestation. Accessed 5/17/10.
3. **Eberhard, M. O., and four others.** 2010. The Mw 7.0 of January 12, 2010: USGS/EERI Advance reconnaissance team report. U.S. Geological Survey Open-File Report 2010-1048, executive summary. Washington, DC.
4. **U.S. Geological Survey.** 2010. *Magnitude 7.0 Haiti region*. Earthquake Hazard Program. www.earthquakes.usgs.gov. Accessed 9/3/10.
5. **Cloud, P.** 1978. *Cosmos, Earth, and Man*. New Haven, CT: Yale University Press.
6. **Ermann, M.** 1927. *Desiderata*. Terre Haute, IN.
7. **Davidson, J. P., Reed, W. E., and Davis, P. M.** 1997. *Exploring Earth*. Upper Saddle River, NJ: Prentice Hall.
8. **Population Reference Bureau.** 2000. World Population Data Sheet. Washington, DC.
9. **Brown, L. R., Flavin, C., and Postel, S.** 1991. *Saving the Planet*. New York: W. W. Norton & Co.
10. **Smil, V.** 1999. How many billions to go? *Nature* 401:429.
11. **Hooke, LeB.** 1994. On the efficiency of humans as geomorphic agents. *GSA Today* 4(9):217, 224–225.
12. **Moncrief, L. W.** 1970. The cultural basis for our environmental crisis. *Science* 170:508–512.
13. **Ellis, W. S.** 1990. A Soviet sea lies dying. *National Geographic* 177(2):73–92.
14. **Lovelock, J.** 1988. *The Ages of Gaia*. New York: W. W. Norton & Co.
15. **Earth Systems Science Committee.** 1988. *Earth Systems Science*. Washington, DC: National Aeronautics and Space Administration.
16. **Paul, R., and Elder, L.** 2003. *Critical Thinking.* Dillon Beach, CA: The Foundation for Critical Thinking.
17. **Leopold, A.** 1949. *A Sand County Almanac*. New York: Oxford University Press.
18. **Diamond, J.** 2005. *Collapse*. London: Penguin Books.
19. **Hunt, T. L.** 2006. Rethinking the fall of Easter Island. *American Scientist* 94(5):412–419.
20. **Rolett, B., and Diamond, J.** 2004. Environmental predictors of pre-European deforestation on Pacific Islands. *Nature* 431:443–446.
21. **Stokstad, E.** 2004. Heaven or hellhole? Islands' destinies were shaped by geography. *Science* 305:1889.
22. **Hunt, T. L, and Lipo, C. P.** 2008. Evidence for a shorter chronology on Rapa Nui (Easter Island). *Journal of Island and Coastal Archaeology* 3:140–148.
23. **Foster, K. R., Vecchia, P., and Repacholi, M. H.** 2000. Science and the precautionary principle. *Science* 5(288):979–981.
24. **Easton, T. A., and Goldfarb, T. D., eds.** 2003. Issue 5: Is the precautionary principle a sound basis for international policy? *Taking Sides, Environmental Issues,* 10th ed., pp. 76–101. Guilford, CT: McGraw-Hill/Dushkin.
25. **Shepard, P.** 1998. *Coming Home to the Pleistocene*. Washington, DC: Island Press.

Chapter 2

1. **Wysession, M.** 1995. The inner workings of Earth. *American Scientist* 83:134–147.
2. **Glatzmaier, G. A.** 2001. *The Geodynamo*. www.es.ucsc.edu/~glatz/geodynamo.html. Accessed 2/21/01.
3. **Fowler, C. M. R.** 1990. *The Solid Earth*. Cambridge: Cambridge University Press.
4. **Le Pichon, X.** 1968. Sea-floor spreading and continental drift. *Journal of Geophysical Research* 73:3661–3697.
5. **Isacks, B. L., Oliver, J., and Sykes, L. R.** 1968. Seismology and the new global tectonics. *Journal of Geophysical Research* 73:5855–5899.
6. **Cox, A., and Hart, R. B.** 1986. *Plate Tectonics*. Boston: Blackwell Scientific Publications.
7. **Keller, E. A., and Pinter, N.** 1996. *Active Tectonics*. Upper Saddle River, NJ: Prentice Hall.
8. **Pinter, N., and Brandon, N. T.** 1997. How erosion builds mountains. *Scientific American* 276(4):60–65.
9. **Dewey, J. F.** 1972. Plate tectonics. *Scientific American* 22:56–68.
10. **Heirtzler, J. R., Le Pichon, X., and Baron, J. G.** 1966. Magnetic anomalies over the Reykjanes Ridge. *Deep Sea Research* 13:427–443.
11. **Cox, A., Dalrymple, G. B., and Doell, R. R.** 1967. Reversals of Earth's magnetic field. *Scientific American* 216(2):44–54.
12. **Claque, D. A., Dalrymple, G. B., and Moberly, R.** 1975. Petrography and K-Ar ages of dredged volcanic rocks from the western Hawaiian Ridge and southern Emperor Seamount chain. *Geological Society of America Bulletin* 86:991–998.
13. **Fichter, L. S.** 1996.Tectonic rock cycles. *Journal of Geoscience Education* 44:134–148.

Chapter 3

1. **Ross, M.** 1990. Hazards associated with asbestos minerals. In *Proceedings of a U.S. Geological Survey workshop on environmental geochemistry,* ed. B. R. Doe, pp. 175–76. U.S. Geological Survey Circular 1033.
2. **Skinner, H. C. W., and Ross, M.** 1994. Minerals and cancer. *Geotimes* 39(1):13–15.
3. **Gribble, C. D., ed.** 1988. *Rutley's Elements of Mineralogy,* 27th ed. Boston: Unwin Hyman.
4. **Nickel, E. H.** 1995. Definition of a mineral. *Mineralogical Magazine* 59:767–768.
5. **Davidson, J. P., Reed, W. E., and Davis, P. M.** 1997. *Exploring Earth*. Upper Saddle River, NJ: Prentice Hall.

6. **Krynine, D. P., and Judd, W. R.** 1957. *Principles of Engineering Geology and Geotechnics*. New York: McGraw-Hill.
7. **Schultz, J. R., and Cleaves, A. B.** 1955. *Geology in Engineering*. New York: John Wiley.
8. **Rogers, J. D.** 1992. Reassessment of the St. Francis Dam failure. In *Engineering Geology Practice in Southern California,* ed. R. Proctor and B. Pipkin, pp. 639–666. Association of Engineering Geologists, Special Publication No. 4.

Chapter 4

1. **Botkin, D. B., and Keller, E. A.** 2005. *Environmental Science,* 5th ed. Hoboken, NJ: John Wiley.
2. **Tallis, J. H.** 1991. *Plant Community History*. London: Chapman and Hall.
3. **Ripple, J. W., and Beschta, Robert L.** 2004. Wolves and the ecology of fear: Can predation risk structure ecosystems? *BioScience* 54(8):755–766.
4. **Dugan, J. E., and Hubbard, D. M.** 2006. Ecological responses to coastal armoring on exposed sandy beaches. *Shore and Beach* 74(1):10–16.
5. **Gould, S. J.** 1993. *The Golden Rule: A Proper Scale for Our Environmental Crisis* in *Eight Little Piggies: Reflections in Natural History*. New York: W. W. Norton.
6. **Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M.** 1997. Human dominator of ecosystems. *Science* 277(5325):494–499.
7. **Riley, A. L.** 1998. *Restoring Streams in Cities*. Washington, DC: Island Press.
8. **Society for Ecological Restoration.** 2004. *The SER International Primer on Ecological Restoration*. www.ser.org. Accessed 3/11/06.
9. **South Florida Water Management District.** *Kissimmee River Restoration*. www.sfwmd.gov. Accessed 3/11/06.
10. **Comprehensive Everglades Restoration Plan.** www.evergladesplan.org. Accessed 3/11/06.

Chapter 5

1. **Dokka, R. K.** 2006. Modern-day tectonic subsidence in coastal Louisiana. *Geology* 34:281–284.
2. **U.S. Army Corps of Engineers.** 2006. *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System,* vol. 1. Executive summary and overview. Washington DC.
3. **Hoyois, P., Below, R., Scheuren, J.-M., and Guha-Sapir, D.** 2007. *Annual Disaster Statistical Review: Numbers and Trends 2006*. Center Brussels, Belgium: University of Louvain for Research on the Epidemiology of Disasters (CRED).
4. **Renner, M., and Chafe, Z.** 2007. *Beyond Disasters*. Washington, DC: Worldwatch Institute.
5. **Advisory Committee on the International Decade for Natural Hazards Reduction.** 1989. *Reducing Disaster's Toll*. Washington, DC: National Academy Press.
6. **White, G. F., and Haas, J. E.** 1975. *Assessment of Research on Natural Hazards*. Cambridge, MA: MIT Press.
7. **Peterson, D. W.** 1986. Volcanoes—Tectonic setting and impact on society. In *Studies in Geophysics: Active Tectonics,* pp. 231–246. Washington, DC: National Academy Press.
8. **Crowe, B. W.** 1986. Volcanic hazards assessment for disposal of high-level radioactive waste. In *Studies in Geophysics: Active Tectonics,* pp. 247–260. Washington, DC: National Academy Press.
9. **Kates, R. W., and Pijawka, D.** 1977. Reconstruction following disaster. In *From Rubble to Monument: The Pace of Reconstruction,* ed. J. E. Haas, R. W. Kates, and M. J. Bowden. Cambridge, MA: MIT Press.
10. **Costa, J. E., and Baker, V. R.** 1981. *Surficial Geology: Building with the Earth*. New York: John Wiley.
11. **Abramovitz, J. N., and Dunn, S.** 1998. *Record Year for Weather-Related Disasters*. Worldwatch Institute, Vital Signs Brief, 98–95.
12. **Magnuson, E.** 1985. A noise like thunder. *Time* 126(13):35–43.
13. **Abramovitz, J. N.** 2001. Averting unnatural disasters. In L. R. Brown, et al., *State of the World 2001,* pp. 123–142. New York: W. W. Norton.
14. **Russell, G.** 1985. Colombia's mortal agony. *Time* 126(21):46–52.
15. **Herd, D. G.** 1986. The 1985 Ruiz Volcano disaster. *EOS, Transactions of the American Geophysical Union,* May 13, 457–460.
16. **IAVCEE Subcommittee on Decade Volcanoes.** 1994. Research on decade volcanoes aimed at disaster prevention. *EOS, Transactions of the American Geophysical Union* 75(30):340, 350.

Chapter 6

1. **U.S. Geological Survey.** 2009. *Magnitude 6 Central Italy.* USGS Earthquake Hazards Program. www.earthquake.usgs.gov.
2. **U.S. Geological Survey.** 2010. *Magnitude 7.0 Haiti Region.* USGS Earthquake Hazards Program. www.earthquake.usgs.gov.
3. **Eberhard, M. O., and four others.** 2010. *The Mw 7.0 of January 12, 2010: USGS/EERI Advance Reconnaissance Team Report*. U.S. Geological Survey Open-File Report 2010-1048. Executive Summary. Washington, DC.
4. **U.S. Geological Survey.** 2010. *Magnitude 8.8 Offshore Mauli, Chili. Haiti region. Earthquake*. USGS Earthquake Hazards Program. www.earthquake.usgs.gov.
5. **Bahan, S., and Mooney, W.** 2008. The cause of China's devastation. *Earth* 53(10):44–47.
6. **U.S. Geological Survey.** 2005. *Magnitude 7.6—Pakistan.* Earthquake Hazards Program. www.earthquake.usgs.gov. Accessed 5/2/06.
7. **Achenbach, J.** 2006. The next big one. *National Geographic* 209(4):120–147.
8. **U.S. Geological Survey.** 2003. *Shake map—A tool for earthquake response*. USGS Fact Sheet FS-087-03.
9. **Hamilton, R. M.** 1980. Quakes along the Mississippi. *Natural History* 89:70–75.
10. **Mueller, K., Champion, J., Guccione, M., and Kelson, K.** 1999. Fault slip rates in the modern New Madrid Seismic Zone. *Science* 286:1135–1138.
11. **U.S. Geological Survey.** 1996. *USGS response to an urban earthquake, Northridge '94*. U.S. Geological Survey Open File Report 96–263.

12. **Melbourne, T. I., and Webb, F. H.** 2003. Slow but not quite silent. *Science* 300:1886.
13. **Bolt, B. A.** 2004. *Earthquakes,* 5th ed. San Francisco: W. H. Freeman.
14. **Jones, R. A.** 1986. New lessons from quake in Mexico. *Los Angeles Times,* September 26.
15. **Hough, S. E., Friberg, P. A., Busby, R., Field, E. F., Jacob, K. H., and Borcherdt, R. D.** 1989. Did mud cause freeway collapse? *EOS, Transactions of the American Geophysical Union* 70(47):1497, 1504.
16. **Hart, E. W., Bryant, W. A., and Treiman, J. A.** 1993. Surface faulting associated with the June 1992 Landers earthquake, California. *California Geology,* January/February, 10–16.
17. **Hanks, T. C.** 1985. *The National Earthquake Hazards Reduction Program: Scientific Status.* U.S. Geological Survey Bulletin 1659.
18. **Press, F.** 1975. Earthquake prediction. *Scientific American* 232:14–23.
19. **Sibson, R. H.** 1981. Fluid flow accompanying faulting: Field evidence and models in earthquake prediction. In *An International Review, Maurice Ewing Ser.,* vol. 4, eds. D. W. Simpson and P. G. Richards, pp. 593–603. Washington, DC: AGU.
20. **Evans, D. M.** 1966. Man-made earthquakes in Denver. *Geotimes* 10:11–18.
21. **Youd, T. L., Nichols, D. R., Helley, E. J., and Lajoie, K. R.** 1975. Liquefaction potential. In *Studies for Seismic Zonation of the San Francisco Bay Region,* ed. R. D. Borcherdt, pp. 68–74. U.S. Geological Survey Professional Paper 941A.
22. **Liu, J. G., and Kusky, T.** 2008. After the quake. *Earth* 53(10):48–51.
23. **Montgomery, D. R., and Manga, M.** 2003. Streamflow and water well response to earthquakes. *Science* 300(5628):2047–2049.
24. **Wang, C. W., Wang, C., and Manga, M.** 2004. Coseismic release of water from mountains: Evidence from the 1999 (Mw=7.5) Chi-Chi, Taiwan earthquake. *Geology* 32(9):769–772.
25. **Hansen, W. R.** 1965. *The Alaskan Earthquake, March 27, 1964: Effects on Communities.* U.S. Geological Survey Professional Paper 542A.
26. **Oppenheimer, D., Beroza, G., Carver, G., Dengler, L., Eaton, J., Gee, L., Gonzales, F., Jayko, A., Li, W. H., Lisowski, M., Magee, M., Marshall, G., Murray, M., McPherson, R., Romanowicz, B., Sataker, K., Simpson, R., Somerville, P., Stein, R., and Valentine, D.** 1993. The Cape Mendocino, California, earthquakes of April, 1992: Subduction at the triple junction. *Science* 262:433–438.
27. **U.S. Geological Survey.** 2004. *Is a powerful quake likely to strike in the next 30 years?* USGS Fact Sheet 039-03, revised in 2004.
28. **Field, E. H., Milner, K. R., and the 2007 Working Group on California Earthquake Probabilities.** 2008. *Forecasting California's Earthquakes—What Can We Expect in the Next 30 Years?* U.S. Geological Survey Fact Sheet 2008–3027.
29. **Scholz, C.** 1997. Whatever happened to earthquake prediction? *Geotimes* 42(3):16–19.
30. **Raleigh, B., et al.** 1977. Prediction of the Haicheng earthquake. *EOS, Transactions of the American Geophysical Union* 58(5):236–272.
31. **Scholz, C. H.** 1990. *The mechanics of earthquakes and faulting.* New York: Cambridge University Press.
32. **Silver, P. G., and Wakita, H.** 1996. A search for earthquake precursors. *Science* 273:77–78.
33. **Rikitakr, T.** 1983. *Earthquake forecasting and warning.* London: D. Reidel.
34. **Hait, M. H.** 1978. Holocene faulting, Lost River Range, Idaho. *Geological Society of America Abstracts with Programs* 10(5):217.
35. **Sieh, K., Stuiver, M., and Brillinger, D.** 1989. A more precise chronology of earthquakes produced by the San Andreas fault in southern California. *Journal of Geophysical Research* 94(B1):603–623.
36. **Akciz, S. O., et al.** 2010.Century-long average time intervals between earthquake ruptures of the San Andreas fault in the Carrizo Plain, California. *Geology* 38(9):787–790.
37. **Reilinger, R., Toksot, N., McClusky, S., and Barka, A.** 2000. 1999 Izmit, Turkey earthquake was no surprise. *GSA Today* 10(1):1–5.
38. **Stein, R. S.** 1999. The role of stress transfer in earthquake occurrence. *Nature* 402(6762):605–609.
39. **State of California.** 1997. *State of California Uniform Building Code.* Chapter 16.
40. **State of California.** 2008. California Geological Survey—Probabilistic seismic hazards assessment—Peak ground acceleration. www.conservation.ca.gov. Accessed 11/30/08.
41. **U.S. Geological Survey.** 2008. Deterministic and scenario ground-motion maps. www.earthquake.usgs.gov/research/hazmaps/scenario.
42. **Wells, D. L., and Coppersmith, K. J.** 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement. *Bulletin of the Seismological Society of America* 84:974–1002.
43. **Eberhart-Phillips, D., and 28 others.** 2003. The 2002 Denali fault earthquake, Alaska: A large magnitude, slip-partitioned event. *Science* 300:1113–1118.
44. **Hendley, J. W., II, and Stauffer, P. H., eds.** 2003. *Rupture in South-Central Alaska—The Denali Earthquake of 2002.* U.S. Geological Survey Fact Sheet 014–03.
45. **Holden, R., Lee, R., and Reichle, M.** 1989. *Technical and Economic Feasibility of an Earthquake Warning System in California.* California Division of Mines and Geology Special Publication 101.
46. **Allen, R.** 2008. At first jolt: Will we have warnings for the next big earthquake? *Earth* 53(10):52–59.
47. **Southern California Earthquake Center.** 1995. *Putting Down Roots in Earthquake Country.* Los Angeles: University of Southern California.

Chapter 7

1. **Subarya, C., Chlieh, M., Prawirodirdjo, L., Avouac, J.-P., Bock, Y., Sieh, K., Meltzner, A. J., Natawidjaja, D. H., and McCaffrey, R.** 2006. Plate-boundary deformation associated with the great Sumatra-Andaman earthquake. *Nature* 440:46–51.

2. **Kerr, R. A.** 2005. Failure to gauge the quake crippled the warning effort. *Science* 307:201.
3. **U.S. Geological Survey.** 2005. *Magnitude 9.1—Off the west coast of northern Sumatra*. U.S. Geological Survey Earthquake Hazards Program. http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav/. Accessed 6/03/07.
4. **Chapman, C.** 2005. The Asian tsunami in Sri Lanka: A personal experience. *EOS, Transactions, American Geophysical Union* 86(2):13–14.
5. **Bendeich, M.** 2005. *Elephants saved tourists from tsunami*. Reuters. http://savetheelephants.org. Accessed 5/25/07.
6. **Achenbach, J.** 2006. The next big one. *National Geographic* 209(4):120–147.
7. **Sieh, K.** 2006. Sumatran megathrust earthquakes: From science to saving lives. *Philosophical Transactions Royal Society* 364:1947–1963.
8. **Jaffe, B. E., and six others.** 2010.*The Limit of Inundation of the September 29, 2009 Tsunami in Tutuila, American Samoa.* U.S. Geological Survey Open File Report 2010–1018.
9. **Bryant, E.** 2001. *Tsunami: The underrated hazards*. New York: Cambridge University Press.
10. **Bolt, B. A.** 2006. *Earthquakes,* 5th ed.; 2006 Centennial update. New York: W. H. Freeman.
11. **U.S. Geological Survey.** 2005. *Life of a Tsunami*. Western Coastal and Marine Geology Program. http://walrus.wr.usgs.gov/tsunami/basics.html. Accessed 5/25/07.
12. **Hokkaido Tsunami Research Group.** 1993. Tsunami devastates Japanese coastal region. *EOS, Transactions American Geophysical Union* 74(37):417–432.
13. **Tappin, D. R., Watts, P., McMurtry, G. M., Lafoy, Y., and Matsumoto, T.** 2001. The Sissano, Papua New Guinea tsunami of July 1998—Offshore evidence of the source mechanism. *Marine Geology* 175:1–23.
14. **Stover, C. W., and Coffman, J. L.** 1993. *Seismicity of the United States, 1958–1989* (revised). U.S. Geological Survey Professional Paper 1527.
15. **Risk Management Solutions.** 2006. *Managing Tsunami Risk in the Aftermath of the 2004 Indian Ocean Earthquake & Tsunami*. Newark, CA: Risk Management Solutions, Inc. http://www.rms.com/Publications/IndianOceanTsunamiReport.pdf. Accessed 5/27/07.
16. **Satake, K., Wang, K., and Atwater, B. F.** 2003. Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions. *Journal of Geophysical Research* 108(B11):148–227, doi:10.1029/2003JB002521.
17. **Nelson, A. R., Atwater, B. F., Bobrowsky, P. T., Bradley, L.-A., Clague, J. J., Carver, G. A., Darienzo, M. E., Grant, W. C., Krueger, H. W., Sparks, R., Stafford, T. W. Jr., and Stuiver, M.** 1995. Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone. *Nature* 378:371–374.
18. **Atwater, B. F.** 1992. Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington. *Journal of Geophysical Research* 97(B2):1901–1919.
19. **Potera, C.** 2005. In disaster's wake: Tsunami lung. *Environmental Health Perspectives* 113(11):A734.
20. **California Seismic Safety Commission.** 2005. *The Tsunami Threat to California; Findings and Recommendations on Tsunami Hazards and Risks.* Report CSSC 05-03.
21. **Danielsen, F., Serensen, M. K., Olwig, M. F., Selvam, V., Parish, F., Burgess, N. D., Hiraishi, T., Karunagaran, V. M., Rasmussen, M. S., Hansen, L. B., Quarto, A., and Suryadiputra, N.** 2005. The Asian tsunami: A protective role for coastal vegetation. *Science* 310:643.
22. **Geist, E. L., and Parsons, T.** 2006. Probabilistic analysis of tsunami hazards. *Natural Hazards* 37:277–314.

Chapter 8

1. **Wright, T. L., and Pierson, T. C.** 1992. *Living with Volcanoes.* U.S. Geological Survey Circular 1073.
2. **Pendick, D.** 1994. Under the volcano. *Earth* 3(3):34–39.
3. **IAVCEE Subcommittee on Decade Volcanoes.** 1994. Research at decade volcanoes aimed at disaster prevention. *EOS, Transactions of the American Geophysical Union* 75(30):340, 350.
4. **Decker, R., and Decker, B.** 2006. *Volcanoes*, 4th ed. New York: W. H. Freeman.
5. **Smith, G. A., and Pun, A.** 2010. *How Does Earth Work,* 2nd ed. Upper Saddle River, NJ: Pearson Prentice Hall.
6. **Fisher, R. V., Heiken, G., and Hulen, J. B.** 1997. *Volcanoes.* Princeton, NJ: Princeton University Press.
7. **Francis, P.** 1983. Giant volcanic calderas. *Scientific American* 248(6):60–70.
8. **Office of Emergency Preparedness.** 1972. *Disaster Preparedness.* 1, 3. Washington, DC.
9. **Crandell, D. R., and Waldron, H. H.** 1969. Volcanic hazards in the Cascade Range. In *Geologic Hazards and Public Problems, Conference Proceedings,* ed. R. Olsen and M. Wallace, pp. 5–18. Office of Emergency Preparedness Region 7, Washington, DC.
10. **Williams, R. S., Jr., and Moore, J. G.** 1973. Iceland chills a lava flow. *Geotimes* 18:14–18.
11. **Neal, C. A., Casadevall, T. J., Miller, T. P., Hendley, J. W., II, and Stauffer, P. H.** 1998. *Volcanic Ash-Danger to Aircraft in the North Pacific*. U.S. Geological Survey Fact Sheet 030–97.
12. **Mazzocchi, M., Hansstein, F., and Ragona, M.** 2010. The 2010 volcanic ash cloud and its financial impact on the European airline industry. *CESifo Forum* 1(1):92–100.
13. **Tilling, R. I.** 2000. Volcano notes. *Geotimes* 45(5):19.
14. **U.S. Geological Survey.** 1997. *Volcanic Air Pollution.* U.S. Geological Survey Fact Sheet 169–97.
15. **U.S. Geological Survey.** 1999. *Pilot Project: Mount Rainier Volcano Lahar Warning System*. http://volcanoes.usgs.gov. Accessed 8/29/06.
16. **Ancochea, E., Fuster, J. M., Ibarrola, E., Cendrero, A., Hernan, F., Cantagrel, J. M., and Jamond, C.** 1990. The volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K-Ar data. *Journal of Volcanology and Geothermal Research* 44(3–4):231–249.
17. **Cantagrel, J. M., Arnaud, N. O., Ancochea, E., Fuster, J. M., and Huertas, M. J.** 1999. Repeated debris avalanches on Tenerife and genesis of Las Cañadas caldera wall (Canary Islands). *Geology* 27(8):739–742.

18. **Watts, A. B., and Masson, D. G.** 1995. A giant landslide on the north flank of Tenerife, Canary Islands. *Journal of Geophysical Research* 100(12):24487–24498.
19. **American Geophysical Union.** 1991. Pinatubo cloud measured. *EOS, Transactions of the American Geophysical Union* 72(29):305–306.
20. **Tilling, R. I.** 2000. Mount St. Helens 20 years later. *Geotimes* 45(5):14–18.
21. **Hammond, P. E.** 1980. Mt. St. Helens blasts 400 meters off its peak. *Geotimes* 25:14–15.
22. **Brantley, S., and Topinka, L.** 1984. *Earthquake Information Bulletin* 16(2).
23. **Pendick, D.** 1995. Return to Mount St. Helens. *Earth* 4(2):24–33.
24. **Francis, P.** 1976. *Volcanoes.* London: Pelican Books.
25. **Kilburn, C. R. J., and Sammonds, P. R.** 2005. Maximum warning times for imminent volcanic eruptions. *Geophysical Research Letters* 32: L24313, doi 10.1029/2005GL024184.
26. **McGuire, B.** 2006. *Hazards and Risk Review 2006*. London: Benfield Hazards Research Centre, University College London.
27. **Richter, D. H., Eaton, J. P., Murata, K. J., Ault, W. U., and Krivoy, H. L.** 1970. *Chronological Narrative of the 1959–60 Eruption of Kilauea Volcano, Hawaii*. U.S. Geological Survey Professional Paper 537E.
28. **Murton, B. J., and Shimabukuro, S.** 1974. Human response to volcanic hazards in Puna District, Hawaii. In *Natural Hazards,* ed. G. F. White, pp. 151–159. New York: Oxford University Press.

Chapter 9

1. **Cred Crunch.** 2008. *Disaster Data* 11. Center for Research on Epidemiology of Disasters (CRED). University of Louvain. Brussels, Belgium.
2. **NOAA.** 2010. *State of Climate Global Hazards, August 2010*. www.ncdc.noaa.gov. Accessed 8/21/10.
3. **Committee on Alluvial Fan Flooding.** 1996. *Alluvial Fan Flooding*. Washington, DC: National Academy Press.
4. **Edelen, G. W., Jr.** 1981. Hazards from floods. In *Facing Geological and Hydrologic Hazards, Earth-Science Considerations,* ed. W. W. Hays, pp. 39–52. U.S. Geological Survey Professional Paper 1240–B.
5. **Keller, E. A., and Capelli, M. H.** 1992. Ventura River flood of February, 1992: A lesson ignored? *Water Resources Bulletin* 28(5):813–831.
6. **Mackin, J. H.** 1948. Concept of the graded river. *Geological Society of America Bulletin* 59:463–512.
7. **Keller, E. A., and Florsheim, J. L.** 1993. Velocity reversal hypothesis: A model approach. *Earth Surface Processes and Landforms* 18:733–748.
8. **Beyer, J. L.** 1974. Global response to natural hazards: Floods. In *Natural Hazards,* ed. G. F. White, pp. 265–274. New York: Oxford University Press.
9. **Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L.** 1958. *Hydrology for Engineers*. New York: McGraw-Hill.
10. **Leopold, L. B.** 1968. *Hydrology for Urban Land Planning*. U.S. Geological Survey Circular 559.
11. **Seaburn, G. E.** 1969. *Effects of Urban Development on Direct Runoff to East Meadow Brook, Nassau County, Long Island, New York*. U.S. Geological Survey Professional Paper 627B.
12. **McCain, J. F., Hoxit, L. R., Maddox, R. A., Chappell, C. F., and Caracena, F.** 1979. *Storm and Flood of July 31–August 1, 1976, in the Big Thompson River and Cache la Poudre River Basins, Larimer and Weld Counties, Colorado*. U.S. Geological Survey Professional Paper 1115A.
13. **Shroba, R. R., Schmidt, P. W., Crosby, E. J., and Hansen, W. R.** 1979. *Storm and Flood of July 31–August 1, 1976, in the Big Thompson River and Cache la Poudre River Basins, Larimer and Weld Counties, Colorado*. U.S. Geological Survey Professional Paper 1115B.
14. **Bradley, W. C., and Mears, A. I.** 1980. Calculations of flows needed to transport coarse fraction of Boulder Creek alluvium at Boulder, Colorado. *Geological Society of America Bulletin,* Part II, 91:1057–1090.
15. **Agricultural Research Service.** 1969. *Water Intake by Soils*. Miscellaneous Publication no. 925.
16. **Strahler, A. N., and Strahler, A. H.** 1973. *Environmental Geoscience*. Santa Barbara, CA: Hamilton Publishing.
17. **Terstriep, M. L., Voorhees, M. L., and Bender, G. M.** 1976. *Conventional Urbanization and Its Effect on Storm Runoff.* Illinois State Water Survey Publication.
18. **Office of Emergency Preparedness.** 1972. *Disaster Preparedness*, 1, 3. Washington, DC.
19. **Mount, J. F.** 1997. *California Rivers and Streams.* Berkeley: University of California Press.
20. **Pinter, N., Thomas, R., and Wlosinski, J. H.** 2001. Assessing flood hazards on dynamic rivers. *Transactions, American Geophysical Union* 82(31):333, 338–339.
21. **Baker, V. R.** 1984. Questions raised by the Tucson flood of 1983. In *Proceedings of the 1984 Meetings of the American Water Resources Association and the Hydrology Section of the Arizona–Nevada Academy of Science,* 211–219.
22. **Baker, V. R.** 1994. Geologic understanding and the changing environment. *Transactions of the Gulf Coast Association of Geological Societies* 44:1–8.
23. **Rahn, P. H.** 1984. Flood-plain management program in Rapid City, South Dakota. *Geological Society of America Bulletin* 95:838–843.
24. **U.S. Department of Commerce.** 1973. *Climatological Data, National Summary* 24(13).
25. **Anonymous.** 1993. The flood of '93. *Earth Observation Magazine,* September:22–23.
26. **Mairson, A.** 1994. The great flood of '93. *National Geographic* 185(1):42–81.
27. **Bell, G. D.** 1993. The great midwestern flood of 1993. *EOS, Transactions of the American Geophysical Union* 74(43):60–61.
28. **Anonymous.** 1993. Flood rebuilding prompts new wetlands debate. *U.S. Water News,* November:10.
29. **U.S. Congress.** 1973. *Stream Channelization: What Federally Financed Draglines and Bulldozers Do to Our Nation's Streams*. House Report No. 93–530. Washington, DC: U.S. Government Printing Office.
30. **Rosgen, D.** 1996. *Applied River Morphology.* Lakewood, CO: Wildland Hydrology.

31. **Pilkey, O. H., and Dixon, K. L.** 1996. *The Corps and the Shore*. Washington, DC: Island Press.
32. **Smith, K., and Ward, R.** 1998. *Floods*. New York: John Wiley.
33. **Bue, C. D.** 1967. *Flood Information for Floodplain Planning*. U.S. Geological Survey Circular 539.
34. **Schaeffer, J. R., Ellis, D. W., and Spieker, A. M.** 1970. *Flood-Hazards Mapping in Metropolitan Chicago*. U.S. Geological Survey Circular 601C.
35. **Baker, V. R.** 1976. Hydrogeomorphic methods for the regional evaluation of flood hazards. *Environmental Geology* 1:261–281.

Chapter 10

1. **Gurrola, L. D., DeVecchio, D. E., and Keller, E. A.** 2010. Rincon Mountain megaslide: La Conchita, Ventura County, California. *Geomorphology* 114(3):311–318.
2. **Jibson, R. W.** 2005. *Landslide Hazards at La Conchita, California*. U.S. Geological Survey Open File Report 2005–1067.
3. **Alan Kropp & Associates.** 2009. *Phase 3 Engineering and Risk Assessment Report: La Conchita Slope Stabilization Project*. Berkeley, CA.
4. **U.S. Geological Survey.** 2004. *Landslide Types and Processes*. Fact Sheet 2004–3072.
5. **Pestrong, R.** 1974. *Slope Stability*. American Geological Institute. New York: McGraw-Hill.
6. **Rahn, P. H.** 1996. *Engineering Geology*, 2nd ed. Upper Saddle River, NJ: Prentice Hall.
7. **Nilsen, T. H., Taylor, F. A., and Dean, R. M.** 1976. *Natural Conditions That Control Landsliding in the San Francisco Bay Region*. U.S. Geological Survey Bulletin 1424.
8. **Campbell, R. H.** 1975. *Soil Slips, Debris Flows, and Rainstorms in the Santa Monica Mountains and Vicinity, Southern California*. U.S. Geological Survey Professional Paper 851.
9. **Terzaghi, K.** 1950. *Mechanisms of Landslides*. Geological Society of America: Application of Geology to Engineering Practice, Berkey Vol.: 83–123. Boulder, CO: Geological Society of America.
10. **Leggett, R. F.** 1973. *Cities and Geology*. New York: McGraw-Hill.
11. **Kiersch, G. A.** 1964. Vaiont Reservoir disaster. *Civil Engineering* 34:32–39.
12. **Swanson, F. J., and Dryness, C. T.** 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the Western Cascade Range, Oregon. *Geology* 7:393–396.
13. **Jones, F. O.** 1973. *Landslides of Rio de Janeiro and the Sierra das Araras Escarpment, Brazil*. U.S. Geological Survey Professional Paper 697.
14. **Leighton, F. B.** 1966. Landslides and urban development. In *Engineering Geology in Southern California,* ed. R. Lung and R. Proctor, pp. 149–197. Los Angeles: Los Angeles Section of the Association of Engineering Geology.
15. **Briggs, R. P., Pomeroy, J. S., and Davies, W. E.** 1975. *Landsliding in Allegheny County, Pennsylvania*. U.S. Geological Survey Circular 728.
16. **Jones, D. K. C.** 1992. Landslide hazards assessment in the context of development. In *Geohazards,* ed. G. J. McCall, D. J. Laming, and S. C. Scott, pp. 117–141. New York: Chapman and Hall.
17. **Slosson, J. E., Yoakum, D. E., and Shuiran, G.** 1986. Thistle, Utah, landslide: Could it have been prevented? In *Proceedings of the 22nd Symposium on Engineering Geology and Soils Engineering*, pp. 281–303.
18. **Piteau, D. R., and Peckover, F. L.** 1978. Engineering of rock slopes. In *Landslides,* ed. R. Schuster and R. J. Krizek. Transportation Research Board, Special Report 176:192–228.
19. **Spiker, E. C., and Gori, P. L.** 2003. *National Landslide Hazards Mitigation Strategy-A Framework for Loss Reduction*. U.S. Geological Survey, Circular 1244.
20. **Poland, J. F., and Davis, G. H.** 1969. Land subsidence due to withdrawal of fluids. In *Reviews in Engineering Geology,* ed. D. J. Varnes and G. Kiersch, pp. 187–269. Boulder, CO: Geological Society of America.
21. **Bull, W. B.** 1974. Geologic factors affecting compaction of deposits in a land subsidence area. *Geological Society of America Bulletin* 84:3783–3802.
22. **Kenny, R.** 1992. Fissures. *Earth* 1(3):34–41.
23. **Cornell, J., ed.** 1974. *It Happened Last Year—Earth Events—1973*. New York: Macmillan.
24. **Dougherty, P. H., and Perlow, M., Jr.** 1987. The Macungie sinkhole, Lehigh Valley, Pennsylvania: Cause and repair. *Environmental Geology and Water Science* 12(2):89–98.
25. **Craig, J. R., Vaughan, D. J., and Skinner, B. J.** 1996. *Resources of the Earth,* 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Chapter 11

1. **McDonald, K. A.** 1993. A geology professor's fervent battle with coastal developers and residents. *Chronicle of Higher Education* 40(7):A8–A9, A12.
2. **National Park Service.** 2010. *Moving the Cape Hatteras Lighthouse*. www.nps.gov. Accessed 8/28/10.
3. **Coates, D. R., ed.** 1973. *Coastal Geomorphology*. Binghamton, NY: Publications in Geomorphology, State University of New York.
4. **Davis, R. E., and Dolan, R.** 1993. Nor'easters. *American Scientist* 81:428–439.
5. **Komar, P. D.** 1998. *Beach Processes and Sedimentation,* 2nd ed. Upper Saddle River, NJ: Prentice Hall.
6. **El-Ashry, M. T.** 1971. Causes of recent increased erosion along United States shorelines. *Geological Society of America Bulletin* 82:2033–2038.
7. **Norris, R. M.** 1977. Erosion of sea cliffs. In *Geologic Hazards in San Diego*, ed. P. L. Abbott and J. K. Victoris. San Diego, CA: San Diego Society of Natural History.
8. **Flanagan, R.** 1993. Beaches on the brink. *Earth* 2(6):24–33.
9. **Briand, J.-L., Nouri, H. R., and Darby, C.** 2008. *Pointe du Hoc Stabilization Study*. College Station: Texas A&M University.
10. **Carter, R. W. G., and Oxford, J. D.** 1982. When hurricanes sweep Miami Beach. *Geographical Magazine* 54(8):442–448.
11. **U.S. Department of Commerce.** 1978. *State of Maryland Coastal Management Program and Final Environmental Impact Statement*. Washington, DC: U.S. Department of Commerce.

12. **Leatherman, S. P.** 1984. Shoreline evolution of North Assateague Island, Maryland. *Shore and Beach,* July, 3–10.
13. **Wilkinson, B. H., and McGowen, J. H.** 1977. Geologic approaches to the determination of long-term coastal recession rates, Matagordo Peninsula, Texas. *Environmental Geology* 1:359–365.
14. **Larsen, J. I.** 1973. *Geology for Planning in Lake County, Illinois*. Illinois State Geological Survey Circular 481.
15. **Buckler, W. R., and Winters, H. A.** 1983. Lake Michigan bluff recession. *Annals of the Association of American Geographers* 73(1):89–110.
16. **White, A. U.** 1974. Global summary of human response to natural hazards: Tropical cyclones. In *Natural Hazards: Local, National, Global,* ed. G. F. White, pp. 255–265. New York: Oxford University Press.
17. **Office of Emergency Preparedness.** 1972. *Disaster Preparedness,* 1, 2. Washington, DC.
18. **Lipkin, R.** 1994. Weather's fury. In *Nature on the Rampage*, pp. 20–79. Washington, DC: Smithsonian Institution.
19. **Rowntree, R. A.** 1974. Coastal erosion: The meaning of a natural hazards in the cultural and ecological context. In *Natural Hazards: Local, National, Global,* ed. G. F. White, pp. 70–79. New York: Oxford University Press.
20. **Baumann, D. D., and Sims, J. H.** 1974. Human response to the hurricane. In *Natural Hazards: Local, National, Global,* ed. G. F. White, pp. 25–30. New York: Oxford University Press.
21. **National Research Council.** 1990. *Managing Coastal Erosion*. Washington, DC: National Academy Press.
22. **Neal, W. J., Blakeney, W. C., Jr., Pilkey, O. H., Jr., and Pilkey, O. H.** 1984. *Living with the South Carolina Shore*. Durham, NC: Duke University Press.
23. **Pilkey, O. H., and Dixon, K. L.** 1996. *The Corps and the Shore*. Washington, DC: Island Press.

Chapter 12

1. **Lewis, J. S.** 1996. *Rain of Iron and Ice*. Reading, MA: Addison-Wesley.
2. **Rubin, A. F.** 2002. *Disturbing the Solar System.* Princeton, NJ: Princeton University Press.
3. **Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E., and Worden, S. P.** 2002. The flux of small near-Earth objects colliding with the Earth. *Nature* 420:294–296.
4. **Cloud, P.** 1978. *Cosmos, Earth and Man*. New Haven, CT: Yale University Press.
5. **Davidson, J. P., Reed, W. E., and Davis, P. M.** 1997. *Exploring Earth.* Upper Saddle River, NJ: Prentice Hall.
6. **Grieve, R., and Cintala, M.** 1999. Planetary impacts. In *Encyclopedia of the Solar System,* ed. P. R. Weissman, L. McFadden, and T. V. Johnson. San Diego, CA: Academic Press.
7. **Williams, S. J., Barnes, P., and Prager, E. J.** 2000. *U.S. Geological Survey coastal and marine geology research—Recent highlights and achievements.* U.S. Geological Survey Circular 1199, p. 28.
8. **Weissman, P. R., McFadden, L., and Johnson, T. V.,** eds. 1999. *Encyclopedia of the Solar System*. San Diego, CA: Academic Press.
9. **Dott, R. H., Jr., and Prothero, D. R.** 1994. *Evolution of the Earth*, 5th ed. New York: McGraw-Hill.
10. **Alvarez, W.** 1997. *T. Rex and the Crater of Doom.* New York: Vintage Books. Random House.
11. **Alvarez, L. W., Alvarez, W., Asaro, F., and Michel, H. V.** 1980. Extraterrestrial cause for Cretaceous–Tertiary extinction. *Science* 208(4448):1095–1108.
12. **Pope, K. O., Ocampo, A. C., and Duller, C. E.** 1991. Mexican site for the K/T impact crater? *Nature* 351:105.
13. **Swisher, C. C., III, Grajales-Nishimura, J. N., Montanari, A., Margolis, S. V., Claeys, P., Alvarez, W., Ranne, P., Cedillo-Pardo, E., Maurrasse, F. J.-N. R., Curtis, G. H., Smit, J., and McWilliams, M. O.** 1992. Ages of 65.0 million years ago from Chicxulub crater melt rocks and Cretaceous-Tertiary boundary tektites. *Science* 257:954–958.
14. **Hildebrand, A. R., Penfield, G. T., Kring, D. A., Pilkington, N., Camargo, Z. A., Jacobsen, S. B., and Boynton, W. V.** 1991. Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatan peninsula, Mexico. *Geology* 19:867–871.
15. **Haynes, C. V., Jr.** 2008. Younger Dryas (Black Mats) and the Rancholabrean termination in North America. *Proceedings of the National Academy of Sciences (PNAS)* 105(18):6520–6525.
16. **Firestone, R. B., and 25 others.** 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the magafauna extinctions and the Younger Dryas cooling. *Proceedings of the National Academy of Sciences (PNS)* 104(41):16016–16021.
17. **Kennett, D. J., and 10 others.** 2008. Wildfire and abrupt ecosystem disruption on California's Northern Channel Islands at the Allerod–Younger Dryas boundary (13.0-12.9ka). *Quaternary Science Reviews* 27:2528–2543.
18. **Kennett, D. J., et al.** 2009. Nanodiamonds in the Younger Dryas boundary sediment layer. *Science* 323:94.
19. **Kennett, D. J., et al.** 2009. Shock-synthesized hexagonal diamonds in Younger Dryas boundary sediments. *Proceedings of the National Academy of Sciences (PNAS)* 10.1073/pnas 0906374106.
20. **Kurabatou, A. V., and 22 others**. 2010. Discovery of a nanodiamond-rich layer in the Greenland ice sheet. *Journal of Glaciology* 56(199):749–759.

Chapter 13

1. **Foxworthy, G. L.** 1978. Nassau County, Long Island, New York—Water problems in humid country. In *Nature to Be Commanded,* ed. G. D. Robinson and A. M. Spieker, pp. 555–568. U.S. Geological Survey Professional Paper 950.
2. **Alley, W. M., Reilly, T. E., and Franke, O. L.** 1999. *Sustainability of Ground-water Resources*. U.S. Geological Survey Circular 1186.
3. **Water Resources Council.** 1978. *The Nation's Water Resources, 1975–2000,* vol. 1. Washington, DC: Water Resources Council.
4. **Gleick, P. H.** 1993. An introduction to global fresh water issues. In *Water in Crisis,* ed. P. H. Gleick, pp. 3–12. New York: Oxford University Press.

5. **Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M.** 1998. *Ground Water and Surface Water. A Single Resource*. U.S. Geological Survey Circular 1139.
6. **Sharp, J. M., Jr., and Banner, J. L.** 1997. The Edwards aquifer: A resource in conflict. *GSA Today* 7(8):1–8.
7. **Loaiciga, H. A., Maidment, D. R., and Valdes, J. B.** 1999. Climate-change impacts in a regional karst aquifer, Texas, U.S.A. *Journal of Hydrology* 227:173–194.
8. **Kenny, J. F., et al.** 2010. *Estimated Use of Water in the United States in 2005.* U.S. Geological Survey Circular 1344.
9. **Hoekstra, A. Y., and Chapagain, A. K.** 2008. *Globalization of Water*. Malden, MA: Blackwell Publishing.
10. **Smil, V.** 2008.Water news: Bad, good and virtual. *American Scientist* 96:399–407.
11. **Hoekstra, A. Y., ed.** 2003. Virtual water trade. *Proceedings of the International Expert Meeting on Virtual Water Trade.* Value of Water Research Report Series 12. Delft, the Netherlands: IHE.
12. **Leopold, L. B.** 1977. A reverence for rivers. *Geology* 5:429–430.
13. **Graf, W. L.** 1985. *The Colorado River*. Washington, DC: Association of American Geographers.
14. **Nash, R.** 1986. Wilderness values and the Colorado River. In *New Courses for the Colorado River,* ed. G. D. Weatherford and F. L. Brown. Albuquerque: University of New Mexico Press.
15. **Hundley, N., Jr.** 1986. The West against itself: The Colorado River—An institutional history. In *New Courses for the Colorado River,* ed. G. D. Weatherford and F. L. Brown. Albuquerque: University of New Mexico Press.
16. **Dolan, R., Howard, A., and Gallenson, A.** 1974. Man's impact on the Colorado River and the Grand Canyon. *American Scientist* 62:392–401.
17. **Lavender, D.** 1984. Great News from the Grand Canyon. *Arizona Highways Magazine* January, 33–38.
18. **Hecht, J.** 1996. Grand Canyon flood a roaring success. *New Scientist* 151:8.
19. **Lucchitta, I., and Leopold, L. B.** 1999. Floods and sandbars in the Grand Canyon. *Geology Today* 9:1–7.
20. **Covich, A. P.** 1993. Water and ecosystems. In *Water in Crisis*, ed. P. H. Gleick, pp. 40–55. New York: Oxford University Press.
21. **Gleick, P. H., ed.** 1993. *Water in Crisis,* Table F.1. New York: Oxford University Press.
22. **Levinson, M.** 1984. Nurseries of life. *National Wildlife* Special Report, February/March, 18–21.
23. **Holloway, M.** 1991. High and dry. *Scientific American* 265(6):16–20.
24. **Brown, L. R.** 2003. *Plan B. Rescuing a Planet Under Stress and a Civilization in Trouble.* New York: W. W. Norton.

Chapter 14

1. **Bowie, P.** 2000. No act of God. *The Amicus Journal* 21(4):16–21.
2. **Mallin, M. A.** 2000. Impacts of industrial animal production on rivers and estuaries. *American Scientist* 88(1):26–37.
3. **Pons, L.** 2005. Blue Lagoons on Pig Farms? *Agriculture Research,* March, 14–15.
4. **Schwarzenbach, R. P., and six others.** 2006. The challenge of micropollutants in aquatic systems. *Science* 313:1072–1077.
5. **Mitch, W. J., Day, J. W., Jr., Gilliam, J. W., Groffman, P. M., Hey, D. L., Randall, G. W., and Wang, N.** 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. *BioScience* 51:373–388.
6. **Oil Spill Issue.** 1989. *Alaska Fish and Game* 21(4).
7. **National Oceanic and Atmospheric Administration.** 2010. *Deepwater Horizon Incident, Gulf of Mexico*. http://response.restoration.noaa.gov.
8. **U.S. Fish and Wildlife Service.** 2009. *Olive Ridley Sea Turtle (*Lepidochelys olivacea*)* www.fws.gov.
9. **National Oceanic and Atmospheric Administration.** 2010. *What's the Story on Oil Spills?* http://response.restoration.noaa.gov.
10. **McGinn, A. P.** 2000. POPs culture. *World Watch*, April 1, 26–36.
11. **Delzer, G. C., Zogorski, J. S., Lopes, T. J., and Basshart, R. L.** 1996. *Occurrence of Gasoline Oxygenate MTBE and BTEX Compounds in Urban Storm Water in the United States, 1991–1995*. U.S. Geological Survey Water Resources Investigations Report 96–4145.
12. **Waldbott, G. L.** 1978. *Health Effects of Environmental Pollutants,* 2nd ed. Saint Louis, MO: C. V. Mosby.
13. **U.S. Geological Survey.** 1995. *Mercury Contamination of Aquatic Ecosystems*. U.S. Geological Survey Fact Sheet FS-216-95.
14. **Author unknown.** *Arsenic Exposure*. http://sos-arsenic.net. Accessed 9/22/06.
15. **Parfit, M.** 1993. Troubled waters run deep. *National Geographic* 184(5A):78–89.
16. **Environmental Protection Agency.** 2002. *American Heritage Rivers, Cuyahoga River*. www.epa.gov/rivers/98river/fscuya.html. Accessed 1/9/02.
17. **Carey, J.** 1984. Is it safe to drink? *National Wildlife*, Special Report, February/March, 19–21.
18. **U.S. Geological Survey.** 1999. *National Water-Quality Assessment Program, Delaware River Basin*. U.S. Geological Survey Fact Sheet FS-056-99.
19. **Moss, M. E., and Lins, H. S.** 1989. *Water Resources in the 21st Century*. U.S. Geological Survey Circular 1030.
20. **Faustini, J. M., et al.** 2009. Assessing stream ecosystem condition in the United States. *EOS, Transactions, American Geophysical Union* 90(36):309–310.
21. **Environmental Protection Agency.** 1991. *Is Your Drinking Water Safe?* EPA 570-9-91-0005.
22. **Jewell, W. J.** 1994. Resource-recovery wastewater treatment. *American Scientist* 82(4):366–375.
23. **Bedient, P. B., Rifai, H. S., and Newell, C. J.** 1994. *Groundwater Contamination*. Englewood Cliffs, NJ: Prentice Hall.
24. **Leeden, F., Troise, F. L., and Todd, D. K.** 1990. *The Water Encyclopedia,* 2nd ed. Chelsea, MI: Lewis Publishers.
25. **U.S. Geological Survey.** 1997. *Predicting the Impact of Relocating Boston's Sewage Outfall*. U.S. Geological Survey Fact Sheet FS-185-97.

26. **American Chemical Society.** 1969. *Clean Our Environment: The Chemical Basis for Action*. Washington, DC: U.S. Government Printing Office.
27. **Breaux, A., Fuber, S., and Day, J.** 1995. Using natural coastal wetland systems: An economic benefit analysis. *Journal of Environmental Management* 44:285–291.
28. **Parizek, R. R., and Myers, E. A.** 1968. Recharge of ground water from renovated sewage effluent by spray irrigation. *Proceedings of the Fourth American Water Resources Conference*, pp. 425–443.
29. **Bastian, R. K., and Benforado, J.** 1983. Waste treatment: Doing what comes naturally. *Technology Review,* February/March, 59–66.
30. **Gaskin, J. W., and Nutter,W. L.** 1989. The effect of irrigation with pretreated wastewater on groundwater quality and elevation at Clayton County, Georgia. In K. J. Hatcher (ed.), *Proceedings of the 1989 Water Resources Conference*. Athens, GA: University of Georgia.
31. **Department of Water Affairs.** 2009. *The Atlantis Water Resources Management Scheme: 30 Years of Artificial Groundwater Recharge.* Pretoria, South Africa: Department of Water Affairs.
32. **Clark, J. F., et al.** 2004. Geochemical imaging of flow near an artificial recharge facility, Orange County, California. *Groundwater* 42(2):167–174.
33. **Hileman, B.** 1995. Rewrite of Clean Water Act draws praise, fire. *Chemical & Engineering News* 73:8.

Chapter 15

1. **Kropschot, S. J., and Johnson, K. M.** 2006. *U.S.G.S. Mineral Resources Program.* U.S. Geological Survey Circular 1289.
2. **Prospectors & Developers Association of Canada.** *Minerals & Use*. www.pdac.ca. Accessed 9/5/06.
3. **Barsotti, A. F.** 1992. Wake up and smell the coffee. *Minerals Today*, October, 12–17.
4. **U.S. Geological Survey.** 2010. *Mineral commodity summaries 2010.* http://minerals.usgs.gov. Accessed 1/15/07.
5. **Brobst, D. A., Pratt, W. P., and McKelvey, V. E.** 1973. *Summary of United States Mineral Resources*. U.S. Geological Survey Circular 682.
6. **Willyard, C.** 2008. Salt of the Earth. *Geotimes* 53(6):22–27.
7. **Kesler, S. F.** 1994. *Mineral Resources, Economics and the Environment*. Upper Saddle River, NJ: Prentice Hall.
8. **Craig, J. R., Vaughan, D. J., and Skinner, B. J.** 1996. *Resources of the Earth,* 2nd ed. Upper Saddle River, NJ: Prentice Hall.
9. **NOAA.** 1977. Earth's crustal plate boundaries: Energy and mineral resources. *California Geology* 30(5):108–109.
10. **Park, C. F., Jr., and MacDiarmid, R. A.** 1970. *Ore Deposits*, 2nd ed. San Francisco: W. H. Freeman.
11. **Smith, G. I., Jones, C. L., Culbertson, W. C., Erickson, G. E., and Dyni, J. R.** 1973. Evaporites and brines. In *United States Mineral Resources,* eds. D. A. Brobst and W. P. Pratt, pp. 197–216. U.S. Geological Survey Professional Paper 820.
12. **Lowenstam, H. A.** 1981. Minerals formed by organisms. *Science* 211:1126–1130.
13. **Cornwall, H. R.** 1973. Nickel. In *United States Mineral Resources,* eds. D. A. Brobst and W. P. Pratt, pp. 437–442. U.S. Geological Survey Professional Paper 820.
14. **Van, N., Dorr, J., Crittenden, M. D., and Worl, R. G.** 1973. Manganese. In *United States Mineral Resources,* eds. D. A. Brobst and W. P. Pratt, pp. 385–399. U.S. Geological Survey Professional Paper 820.
15. **McGregor, B. A., and Lockwood, M.** (no date). *Mapping and Research in the Exclusive Economic Zone.* U.S. Geological Survey and NOAA.
16. **U.S. Department of the Interior, Bureau of Mines.** 1991. *Research 92: Biotechnology—Using Nature to Clean Up Waste.* 128.115(992):16–21.
17. **Silva, M. A.** 1988. Cyanide heap leaching in California. *California Geology* 41(7):147–156.
18. **Woodbury, R.** 1998. The giant cup of poison. *Time* 151(12):4.
19. **Pettyjohn, W. A.** 1972. Nothing is without poison. In *Man and His Physical Environment,* ed. G. D. McKenzie and R. O. Utgard, pp. 109–110. Minneapolis: Burgess Publishing.
20. **Takahisa, H.** 1971. *Discussion on Environmental Geochemistry in Health and Disease,* ed. H. L. Cannon and H. C. Hupps, pp. 221–222. Geological Society of America Memoir 123.
21. **Alpers, C. N., Hunerlach, M. P., May, J. T., and Hothem, R. L.** 2005. *Mercury Contamination from Historical Gold Mining in California.* U.S. Geological Survey Fact Sheet FS-2005–3014.
22. **Jeffers, T. H.** 1991. Using microorganisms to recover metals. *Minerals Today,* June, 14–1.
23. **Haynes, B. W.** 1990. Environmental technology research. *Minerals Today,* May, 13–17.
24. **Sullivan, P. M., Stanczyk, M. H., and Spendbue, M. J.** 1973. *Resource Recovery from Raw Urban Refuse.* Report of Investigations 7760. Washington, DC: U.S. Bureau of Mines.
25. **Davis, F. F.** 1972. Urban ore. *California Geology*, May, 99–112.
26. **U.S. Geological Survey.** 2007. *Minerals Yearbook 2006—Recycling Metals*. http://minerals.usgs.gov. Accessed 1/15/07.
27. **Brown, L., Lenssen, N., and Kane, H.** 1995. Steel recycling rising. In *Vital Signs 1995.* Washington, DC: Worldwatch Institute.
28. **Wellmar, F. W., and Kosinowoski, M.** 2003. Sustainable development and the use of non-renewable sources. *Geotimes* 48(12):14–17.

Chapter 16

1. **Kerr, R. A.** 2010. Do we have energy for the next transition? *Science* 329(5993):780–781.
2. **Wiffles, R. H., and Barbosa, M. J.** 2010. An outlook on microalgal biofuels. *Science* 329(5993):796–799.
3. **Butti, K., and Perlin, J.** 1980. *The Golden Thread: 2500 Years of Solar Architecture and Technology*. Palo Alto, CA: Cheshire Books.
4. **McKibben, B.** 2007. Energizing America. *Sierra* 92:1, 30–38, 112–113.

5. **Alekett, K.** 2006. Oil: A bumpy road ahead. *World Watch* 19:1, 10–12.
6. **Cavanay, R.** 2006. Global oil about to peak? A recurring myth. *World Watch* 19: 1, 13–15.
7. **Greb, S. F., Cortland, R. E., Douglas, E. P., and Alexander, R. P.** 2006. *Coal and the Environment.* Alexandria, VA: American Geophysical Institute.
8. **Craig, J. R., Vaughan, D. J., and Skinner, B. J.** 1996. *Resources of the Earth*. Upper Saddle River, NJ: Prentice Hall.
9. **Garbini, S., and Schweinfurth, S. P., eds.** 1986. U.S. Geological Survey Circular 979.
10. **U.S. Environmental Protection Agency.** 1973. *Processes, Procedures and Methods to Control Pollution from Mining Activities*. EPA-430/9-73-001.
11. **Webber, M. E.** 2009. Coal-to-liquids: The good, the bad and the ugly. *Earth* 54(4):44–47.
12. **Berlin Snell, M.** 2007. Can coal be clean? *Sierra* 92:1, 32–33.
13. **Environmental Protection Agency.** 2009. *TVA Kingston Fossil Plant Fly Ash Release: EPA's Response*. www.epa.gov/region4/kingston. Accessed 3/15/09.
14. **Kesler, S. E.** 1994. *Mineral Resources, Economics and the Environment*. New York: Macmillan.
15. **Vendetti, J.** 2001. Storing coal slurry. *Geotimes* 46(12):7.
16. **McCabe, P. J., Gautier, D. L., Lewan, M. D., and Turner, C.** 1993. *The future of energy gases*. U.S. Geological Survey Circular 1115.
17. **Canadian Centre for Energy.** *How Is Oil Formed?* www.centreforenergy.com. Accessed 3/16/09.
18. **Nuccio, V.** 1997. *Coal-Bed Methane—An Untapped Energy Resource and an Environmental Concern*. U.S. Geological Survey Fact Sheet FS-019-97.
19. **Milici, R. C., and Swezey, C. S.** 2006. *Assessment of Appalachian Basin Oil and Gas Resources: Devonian Shale-Middle and Upper Paleozoic Total Petroleum System*. U.S. Geological Survey Open File Report 2006–1237.
20. **Suess, E., Bohrmann, G., Greinert, J., and Lauch, E.** 1999. Flammable ice. *Scientific American* 28(5):76–83.
21. **Dyni, J. R.** 2006. *Geology and Resources of Some World Oil-Shale Deposits*. U.S. Geological Survey Scientific Investigations Report 2005–5294.
22. **Kunzig, R.** 2009. The Canadian oil boom. *National Geographic* 215:3, 34–59.
23. **British Petroleum Company.** 2010. *B. P. Statistical Review of World Energy 2009*.
24. **Youngquist, W.** 1998. Spending our great inheritance. Then what? *Geotimes* 43(7):24–27.
25. **Edwards, J. D.** 1997. Crude oil and alternative energy production forecast for the twenty-first century: The end of the hydrocarbon era. *American Association of Petroleum Geologists Bulletin* 81(8):1292–1305.
26. **Krajick, K.** 2001. Long-term data show lingering effects from acid rain. *Science* 292:195–96.
27. **Jenkins, J., Ron, K., Driscoll, C., and Buerkett, C.** 2007. *Acid Rain in the Adirondacks.* Ithaca, NY: Comstock Publishing Associates.
28. **Finch, W. I.** 2002. *Uranium Fuel for Nuclear Energy*. U.S. Geological Survey Bulletin 2179-A.
29. **Brenner, D. J.** 1989. *Radon: Risk and Remedy*. New York: W. H. Freeman.
30. **O'Leary, J.** 1997. *A new reactor for a new Europe.* Mechanical Engineering Power (supplement). *Mechanical Engineering*. www.memagazine.org. Accessed 11/3/10.
31. **Energy Information Administration.** 2009. *U.S. Nuclear Reactors*. www.eia.doe.gov/cneaf/nuclear. Accessed 2/25/09.
32. **MacLeod, G. K.** 1981. Some public health lessons from Three Mile Island: A case study in chaos. *Ambio* 10:18–23.
33. **Anspaugh, L. R., Catlin, R. J., and Goldman, M.** 1988. The global impact of the Chernobyl reactor accident. *Science* 242:1513–1518.
34. **Balter, M.** 1995. Chernobyl's thyroid cancer toll. *Science* 270:1758.
35. **Fletcher, M.** 2000. The last days of Chernobyl. *The (London) Times* 2, November 14, 3–5.
36. **Rauber, P.** 2007. Why not nukes? *Sierra* 92:1, 37.
37. **Massachusetts Institute of Technology.** 2003. *The Future of Nuclear Power*. Cambridge, MA: Massachusetts Institute of Technology.
38. **Grimes, R. W., and Nuttall, W. J.** 2010. Generating the option of a two-stage nuclear renaissance period. *Science* 329(5993):799–803.
39. **Office of Industry Relations.** 1974. *The Nuclear Industry, 1974*. Washington, DC: U.S. Government Printing Office.
40. **Fischer, J. N.** 1986. *Hydrologic Factors in the Selection of Shallow Land Burial for the Disposal of Low-Level Radioactive Waste*. U.S. Geological Survey Circular 973.
41. **Weart, W. D., Rempe, M. T., and Powers, D. W.** 1998. The waste isolation plant. *Geotimes,* October, pp. 14–19.
42. **U.S. Department of Energy.** *Waste Isolation Pilot Plant, Carlsbad, New Mexico.* http://www.wipp.energy.gov. Accessed 11/21/10.
43. **Heiken, G.** 1979. Pyroclastic flow deposits. *American Scientist* 67:564–71.
44. **U.S. Department of Energy.** 1990. *Yucca Mountain Project: Technical Status Report*. DE90015030.
45. **Bredehoeft, J. D., England, A. W., Stewart, D. B., Trask, J. J., and Winograd, I. J.** 1978. *Geologic Disposal of High-Level Radioactive Wastes—Earth Science Perspectives*. U.S. Geological Survey Circular 779.
46. **Duffield, W. A., and Sass, J. H.** 2003. *Geothermal Energy—Clean Power from the Earth's Heat*. U.S. Geological Survey Circular 1249.
47. **Wald, M. L.** 2009. The power of renewables. *Scientific American* 300(3):57–61.
48. **Flavin, C., and Dunn,S**. 1999. Reinventing the energy system. In *State of the World 1999: A Worldwatch Institute Report on Progress Toward a Sustainable Society,* ed. L. R. Brown, et al. New York: W. W. Norton.
49. **Berger, J. J.** 2000. *Beating the Heat*. Berkeley, CA: Berkeley Hills Books.
50. **Miller, E. W.** 1993. *Energy and American Society. A Reference Handbook.* Santa Barbara, CA: ABC-CLIO.
51. **Mayur, R., and Daviss, B.** 1998. The technology of hope. *The Futurist,* October, 46–51.
52. **Brown, L. R.** 1999. Crossing the threshold. *Worldwatch,* March–April, 12–22.

53. **Quinn, R.** 1997. Sunlight brightens our energy future. *The World and I*, March, 156–163.
54. **Hunt, S. C., Sawin, J. L., and Stair, P.** 2006. *Cultivating Renewable Alternatives to Oil.* In *State of the World 2006*, ed. W. Stark, pp. 61–77. New York: W. W. Norton.
55. **Seth, D.** 2001. *Hydrogen Futures: Toward a Sustainable Energy System.* Worldwatch Paper 157. Washington, DC: Worldwatch Institute.
56. **Kartha, S., and Grimes, P.** 1994. Fuel cells: Energy conversion for the next century. *Physics Today* 47:54–61.
57. **Haggin, J.** 1995. Fuel-cell development reaches demonstration stage. *Chemical & Engineering News* 73:28–30.
58. **Alward, R., Eisenbart, S., and Volkman, J.** 1979. *Micro-Hydro Power: Reviewing an Old Concept*. Washington, DC: U.S. Department of Energy, National Center for Appropriate Technology.
59. **Zich, R.** 1997. China's Three Gorges: Before the flood. *National Geographic* 192(3):2–33.
60. **U.S. Department of Energy.** 2010. Wind powering America. www.windpoweringamerica.gov
61. **Cuellar, A. D., and Webber, M. E.** 2008. Cow power: The energy and emissions benefits of converting manure to biogas. *Environmental Research Letters* 3(034002):1–8.
62. **Miller, P.** 2009. Saving energy. *National Geographic* 215:3, 60-81.
63. **Lindley, D.** 2009. The energy should always work twice. *Nature* 458(7235):138–141.
64. **Lovins, A. B.** 1979. *Soft Energy Paths: Towards a Durable Peace*. New York: Harper & Row.
65. **Duval, J.** 2007. The fix. *Sierra* 92:1, 40–41.
66. **Flafin, C.** 2008. *Low-Carbon Energy: A Roadmap*. Worldwatch report 178. Washington, DC: Worldwatch Institute.
67. **Sorkhabi, R.** 2008. What drives oil and gasoline prices? *Earth* 53(11):36–43.

Chapter 17

1. **Weiser, K.** 2009. *Missouri Legends: Ill-Fated Times Beach*. www.legendsofamerica.com/mo-timesbeach.html. Accessed 9/28/10.
2. **Grady, D.** 1983. The dioxin dilemma. *Discover*, May, 78–83.
3. **Roberts, L.** 1991. More pieces of the dioxin puzzle. *Science* 254:377.
4. **Montgomery, D.** 2007. Is agriculture eroding civilization's foundation? *GSA Today* 17(10):4–10.
5. **Montgomery, D. R**. 2007. Dirt: *The Erosion of Civilizations*. Berkeley, California: University of California Press.
6. **Vitousek, P. M., Chadwick, O. A., Crews, T. E., Fownes, J. H., Hendricks, D. M., and Herbert, D.** 1997. Soil and ecosystem development across the Hawaiian Islands. *GSA Today* 7(9):1–10.
7. **Birkland, P. W.** 1984. *Soils and Geomorphology.* New York: Oxford University Press.
8. **Brady, N. C., and Weil, R. R.** 1996. *The Nature and Properties of Soils,* 11th ed. Upper Saddle River, NJ: Prentice Hall.
9. **Miller, R. W., and Gardiner, D. T.** 1998. *Soils in Our Environment,* 8th ed. Upper Saddle River, NJ: Prentice Hall.
10. **Keller, E. A., Bonkowski, M. S., Korsch, R. J., and Shlemon, R. J.** 1982. Tectonic geomorphology of the San Andreas fault zone in the southern Indio hills, Coachella Valley, California. *Geological Society of America Bulletin* 93:46–56.
11. **Van der Woerd, J., Klinger, Y., Sieh, K., Tapponnier, P., Ryerson, F. J., and Meriaux, A. S.** 2006. Long-term slip rate of the southern San Andreas Fault from 10Be-26Al surface exposure dating of an offset alluvial fan. *Journal of Geophysical Research* 11 B04407: 10.1029/2004 JB00359.
12. **Anonymous.** 1979. *Environmentally Sound Small-Scale Agricultural Projects*. Mt. Rainier, MD: Mohonk Trust, Vita Publications.
13. **Olson, G. W.** 1981. *Soils and the Environment.* New York: Chapman and Hall.
14. **Singer, M. J., and Munns, D. N.** 1996. *Soils,* 3rd ed. Upper Saddle River, NJ: Prentice Hall.
15. **Krynine, D. P., and Judd, W. R.** 1957. *Principles of Engineering Geology and Geotechnics*. New York: McGraw-Hill.
16. **Pestrong, R.** 1974. *Slope Stability.* New York: American Geological Institute and McGraw-Hill.
17. **Flawn, P. T.** 1970. *Environmental Geology.* New York: Harper & Row.
18. **Hart, S. S.** 1974. Potentially swelling soil and rock in the Front Range urban corridor. *Environmental Geology* 7. Denver: Colorado Geological Survey.
19. **Mathewson, C. C., Castleberry, J. P., II, and Lytton, R. L.** 1975. Analysis and modeling of the performance of home foundations on expansive soils in central Texas. *Bulletin of the Association of Engineering Geologists* 17(4):275–302.
20. **Jones, D. E., Jr., and Holtz, W. G.** 1973. Expansive soils: The hidden disaster. *Civil Engineering*, August, 49–51.
21. **Wischmeier, W. H., and Meyer, L. D.** 1973. Soil erodibility on construction areas. In *Soil Erosion: Causes, Mechanisms, Prevention and Control,* pp. 20–29. Highway Research Board Special Report 135. Washington, DC: Highway Research Board.
22. **Dunne, T., and Leopold, L. B.** 1978. *Water in Environmental Planning.* San Francisco: W. H. Freeman.
23. **Robinson, A. R.** 1973. Sediment: Our greatest pollutant? In *Focus on Environmental Geology,* ed. R. W. Tank, pp. 186–192. New York: Oxford University Press.
24. **Yorke, T. H.** 1975. Effects of sediment control on sediment transport in the northwest branch Anacostia River Basin, Montgomery County, Maryland. *U.S. Geological Survey Journal of Research* 3:487–494.
25. **Botkin, D. B., and Keller, E. A.** 2009. *Environmental Science,* 7th ed. New York: John Wiley.
26. **Wilshire, H. G., and Nakata, J. K.** 1976. Off-road vehicle effects on California's Mojave Desert. *California Geology* 29:123–132.
27. **Wilshire, H. G., et al.** 1977. *Impacts and Management of Off-Road Vehicles.* Report to the Committee on Environment and Public Policy. Washington, DC: Geological Society of America.
28. **Hazen, T. C.** 1995. Savanna River site—A test bed for cleanup technologies. *Environmental Protection,* April, 10–16.

Chapter 18

1. **Mann, M. E., and 8 others.** 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326:1256–1260.
2. **Fagan, B. M.** 2008. *The Great Warming: Climate Change and the Rise and Fall of Civilizations*. New York: Bloomsbury Press.
3. **National Research Council.** 2006. *Surface Temperature Reconstructions for the Last 2,000 Years*. Washington, DC: National Academy Press.
4. **National Aeronautics and Space Administration (NASA).** 1990. *EOS: A Mission to Planet Earth*. Washington, DC: NASA.
5. **Luthi, D., et al.** 2008. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* 453:379–382.
6. **Hansen, J.** 2004. Defusing the global warming time bomb. *Scientific American* 290(3):68–77.
7. **IPCC.** 2007. *The Physical Science Basis: Working Group I. Contribution to the Fourth Assessment Report*. New York: Cambridge University Press.
8. **Ruddiman, W. F.** 2008. *Earth's Climate Past and Future,* 2nd ed. New York: W. H. Freeman and Company.
9. **NOAA.** 2009. Paleo proxy data. In *Introduction to Paleoclimatology*. www.ncdc.noaa.gov. Accessed 3/24/10.
10. **Brook, E.** Paleoclimate: Windows on the greenhouse. *Nature* 453:291–292.
11. **Environmental Protection Agency.** 2010. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008.*
12. **Hansen, J., and Sato, M.** 2004. Greenhouse gas growth rates. *Proceedings of the National Academy of Science* 101:16109–16114.
13. **Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D., and Medina-Elizade, M.** 2006. Global temperature change. *Proceedings of the National Academy of Science* 103:14288–14293.
14. **Kennett, J.** 1982. *Marine Geology*. Englewood Cliffs, NJ: Prentice Hall.
15. **Hansen, J., et al.** 2005. Efficacy of climate forcing. *Journal of Geophysical Research* 110, D18104. doi: 10.1029/2005 JD 005776.
16. **Hansen, J.** 2003. *Can We Defuse the Global Warming Time Bomb?* Edited version of presentation to the Council on Environmental Quality, June 12. Washington DC. www.naturalscience.com.
17. **Broecker, W.** 1997. Will our ride into the greenhouse future be a smooth one? *GSA Today* 7(5):1–7.
18. **Seager, R.** 2006. The source of Europe's mild climate. *American Scientist* 94:334–341.
19. **Crowley, T. J.** 2000. Causes of climate change over the past 1000 years. *Science* 289:270–277.
20. **Foukal, P., Frohlich, C., Spruit, H., and Wigley, T.** 2006. Variations in solar luminosity and their effect on the earth's climate. *Nature* 443(14):161–166.
21. **Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley, J. A. J., Hansen, J. E., and Hofmann, D. J.** 1992. Climate forcing by anthropogenic aerosols. *Science* 255:423–430.
22. **Kerr, R. A.** 1995. Study unveils climate cooling caused by pollutant haze. *Science* 268:802.
23. **McCormick, P. P., Thomason, L. W., and Trepte, C. R.** 1995. Atmospheric effects of the Mt. Pinatubo eruption. *Nature* 373:399–436.
24. **Bell, R. E.** 2008. The Unquiet ice. *Scientific American* 298(2):60–67.
25. **Kohler, J.** 2007. Lubricating lakes. *Nature* 445:830.
26. **Appenzeller, T.** 2007. Big thaw. *National Geographic* 211(6):56–71.
27. **Ferrians, O. J., Jr., Kachadoorian, R., and Greene, G. W.** 1969. *Permafrost and Related Engineering Problems in Alaska*. U.S. Geological Survey Professional Paper 678.
28. **Pelto, M. S.** 1996. Recent changes in glacier and alpine runoff in the North Cascades, Washington. *Hydrological Processes* 10:1173–1180.
29. **U.S. Geological Survey.** *USGS Repeat Photography Project Documents Retreating Glaciers in Glacier National Park.* www.nrmsc.usgs.gov/repeatphoto/. Accessed 4/10/09.
30. **Stroeve, J., and 7 others.** 2008. Arctic sea ice extent plummets in 2007. *EOS, Transactions, American Geophysical Union* 89(2):13–14.
31. **Steig, E. J., and 5 others.** 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature* 457:459–462.
32. **Davis, C. H., and 4 others.** 2005. Snowfall-driven growth in East Antarctic ice sheet mitigates recent sea-level rise. *Science* 308(5739):1898–1901.
33. **Monagham, A. J., and 15 others.** 2006. Insignificant change in Antarctic snowfall since the International Geophysics year. *Science* 313(5788):827–831.
34. **Bloom, A. A., et al.** 2010. Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data. *Science* 327(5963):322–325.
35. **Mainguet, M.** 1994. *Desertification,* 2nd ed. Berlin: Springer-Verlag.
36. **Goudie, A.** 1984. *The Nature of the Environment,* 3rd ed. Oxford, UK: Blackwell Scientific.
37. **Grainger, A.** 1990. *The Threatening Desert*. London: Earthscan Publications.
38. **Oberlander, T. M.** 1994. Global deserts: A geomorphic comparison. In *Geomorphology of Desert Environments*, ed. A. D. Abrahams and A. J. Parsons, pp. 13–35. London: Chapman and Hall.
39. **Dregne, H. E.** 1983. Desertification of arid lands. *Advances in Desert and Arid Land Technology and Development,* vol. 3. Chur, Switzerland: Harwood Academic Publishers.
40. **Sheridan, D.** 1981. *Desertification of the United States*. Washington, DC: Council on Environmental Quality.
41. **University Corporation for Atmospheric Research.** 1994. *El Niño and Climate Prediction*. Washington, DC: NOAA Office of Global Programs.
42. **Dennis, R. E.** 1984. A revised assessment of worldwide economic impacts: 1982–1984 El Niño/southern oscillation event. *EOS, Transactions of the American Geophysical Union* 65(45):910.
43. **Canby, T. Y.** 1984. El Niño's ill winds. *National Geographic* 165:144–181.
44. **Philander, S. G.** 1998. Who is El Niño? *EOS, Transactions of the American Geophysical Union* 79(13):170.

45. **Titus, J. G., Leatherman, S. P., Everts, C. H., Moffatt and Nichol Engineers, Kriebel, D. L., and Dean, R. G.** 1985. *Potential Impacts of Sea Level Rise on the Beach at Ocean City, Maryland*. Washington, DC: U.S. Environmental Protection Agency.
46. **Anderson, D. R., and 5 others**. 2009. *Coastal Sensitivity to Sea Level Rise*. Washington, DC: U.S. Climate Change Program.
47. **Dickinson, W. R.** 2009. Pacific atoll living—How long already and until when? *GSA Today* 19(3):4–10.
48. **Kumar, M.** 2007. Alaska melting into the sea. *Geotimes* 52(9):8–9.
49. **U.S. Climate Change Program.** 2008. *Climate Change and Ecosystems*. Washington, DC: U.S. Climate Change Program.
50. **Union of Concerned Scientists.** 2003. *Early Warning Signs: Coral Reef Bleaching*. www.ucsusa.org. Accessed 4/10/09.
51. **Doney, S. C**. 2010. The growing human imprint on coastal and open-ocean biogeochemistry. *Science* 238:1512–1516.
52. **Hoegh-Gulburg, O., and Bruno, J. F.** 2010. The impact of climate change on the world's marine ecosystems. *Science* 328:1523–1528.
53. **Hardt, M. J., and Safina, C.** 2010. Threatening ocean life from the inside out. *Scientific American* 303(2):66–73.
54. **Appell, D.** 2009. Can assisted migration save species from global warming? *Scientific American* 30(3):378–380.
55. **Botkin, D. B., and 18 others.** 2007. Forecasting effects of global warming on biodiversity. *BioScience* 57(3):227–236.
56. **Lea, D. W.** 2004. The 100,000 year cycle in tropical SST, greenhouse forcing, and climate sensitivity. *Journal of Climate* 17(11):2170–2179.
57. **Friedman, S. J.** 2003. Storing carbon in Earth. *Geotimes* 48(3):16–20.
58. **Nameroff, T.** 1997. The climate change debate is heating up. *GSA Today* 7(12):11–13.
59. **Bartlett, K.** 2003. Demonstrating carbon sequestration. *Geotimes* 48(3):22–23.
60. **Flavin, C.** 2008. *Low-Carbon Energy*. Worldwatch Report 178. Washington, DC: Worldwatch Institute.
61. **McGeehin, J. P., Barron, J. A., Anderson, D. M., and Verardo, D. J. 2008.** *Abrupt Climate Change*. Final Report, Synthesis and Assessment Product 3.4. U.S. Climate Change Science Program.
62. **Toon, O. B., and Turco, R. P.** 1991. Polar stratospheric clouds and ozone depletion. *Scientific American* 264(6):68–74.
63. **Molina, M. J., and Rowland, F. S.** 1974. Stratospheric sink for chlorofluoromethanes: Chlorine atom-catalyzed destruction of ozone. *Nature* 249:810–812.

Chapter 19

1. **Brenner, D. J.** 1989. *Radon: Risk and Remedy*. New York: W. H. Freeman.
2. **Egginton, J.,** 1989. Menace of Whispering Hills. *Audubon*, January, pp. 25–28.
3. **Sauer, H. I., and Brand, F. R.** 1971. Geographic patterns in the risk of dying. In *Environmental Geochemistry in Health,* ed. H. L. Cannon and H. C. Hopps, pp. 131–150. Boulder, CO: Geological Society of America Memoir 123.
4. **Selinus, O. ed.** 2005. *Essentials of Medical Geology*. Burlington, MA: Elsevier Academic Press.
5. **Bylinsky, G.** 1972. Metallic menaces. In *Man, Health and Environment,* ed. B. Hafen, pp. 174–185. Minneapolis: Burgess Publishing.
6. **Hong, S., Candelone, J.-P., Patterson, C. C., and Boutron, C. F.** 1994. Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilizations. *Science* 265:1841–1843.
7. **Warren, H. V., and Delavault, R. E.** 1967. A geologist looks at pollution: Mineral variety. *Western Mines* 40:23–32.
8. **Needleman, H. L., Riess, J. A., Tobin, M. J., Biesecker, G. E., and Greenhouse, J. B.** 1996. Bone lead levels and delinquent behavior. *Journal of the American Medical Association* 275:363–369.
9. **Hopps, H. C.** 1971. Geographic pathology and the medical implications of environmental geochemistry. In *Environmental Geochemistry in Health,* ed. H. L. Cannon and H. C. Hopps, pp. 1–11. Boulder, CO: Geological Society of America Memoir 123.
10. **Pettyjohn, W. A.** 1972. No thing is without poison. In *Man and His Physical Environment,* ed. G. D. McKenzie and R. O. Utgard, pp. 109–110. Minneapolis: Burgess Publishing.
11. **Takahisa, H.** 1971. In *Environmental Geochemistry in Health and Disease*, ed. H. L. Cannon and H. C. Hopps, pp. 221–222. Boulder, CO: Geological Society of America Memoir 123.
12. **Kobayashi, J.** 1957. On the geographical relationship between the chemical nature of river water and death-rate of apoplexy. *Berichte des Ohara Institute für Landwirtschaftliche Biologie* 11:12–21.
13. **Rubonowitz-Lundun, E., and Hiscock, K. M.** 2005. Water hardness and health effects. In *Essentials of Medical Geology,* ed. O. Selinus, Ch. 13. Burlington, MA: Elsevier Academic Press.
14. **Schroeder, H. A.** 1966. Municipal drinking water and cardiovascular death-rates. *Journal of the American Medical Association* 195:125–129.
15. **Bain, R. J.** 1979. Heart disease and geologic setting in Ohio. *Geology* 7:7–10.
16. **Klusman, R. W., and Sauer, H. I.** 1975. *Some Possible Relationships of Water and Soil Chemistry to Cardiovascular Diseases in Indiana*. Boulder, CO: Geological Society of America Special Paper 155.
17. **Appleton, J. D.** 2005. Radon in Air and Water. In *Essentials of Medical Geology*, ed. O. Selinus, Ch. 10. Burlington, MA: Elsevier Academic Press.
18. **U.S. Environmental Protection Agency.** 1986. *A Citizen's Guide to Radon*. OPA-86-004.
19. **Alavanja, M. C., Brownson, R. C., Lubin, J. H., Berger, E., Chang, J. C., and Boice, J. D., Jr.** 1994. Residential radon exposure and lung cancer among non-smoking women. *Journal of the National Cancer Institute* 80(24):1829–1837.
20. **Pershagen, G., Akerblom, G., Axelson, O., Clavensjo, B., Damber, L., Desai, G., Enflo, A., Lagarde, F., Mellander, H., Svartengren, M., and Swedjemark, G. A.** 1994. Residential radon exposure and lung cancer in Sweden. *New England Journal of Medicine* 330(3):159–164.

21. **Gates, A. E, and Gunderson, L. C. S.** 1989. Role of ductile shearing in the concentration of radon in the Brookneal Zone, Virginia. *Geology* 17:391–394.
22. **Hurlburt, S.** 1989. Radon: A real killer or just an unsolved mystery? *Water Well Journal*, June, 34–41.
23. **University of Maine and Maine Department of Human Services.** 1983. Radon in water and air. *Resource Highlights,* February.
24. **U.S. Environmental Protection Agency.** 1986. *Radon Reduction Techniques for Detached Houses*. EPA 625/5-86-019.
25. **U.S. Environmental Protection Agency.** 1988. *Radon Resistant Residential New Construction*. EPA 600/8-88/087.
26. **Store, R.** 1993. Radon risk up in the air. *Science* 261:1515.
27. **American Lung Association.** 2001. *State of the Air 2000*.
28. **Godish, T.** 1991. *Air Quality*, 2nd ed. Chelsea, MI: Lewis Publishers.
29. **National Park Service.** 1984. *Air Resources Management Manual*.
30. **U.S. Environmental Protection Agency.** 2006. *National-Scale Air Toxics Assessment for 1999: Estimated Emissions, Concentrations and Risks*. www.epa.gov. Accessed 4/10/06.
31. **Pope, C. A., III, Bates, D. V., and Raizenne, M. E.** 1995. Health effects of particulate air pollution: Time for reassessment? *Environmental Health Perspectives* 103:472–480.
32. **Pittock, A. B., Frakes, L. A., Jenssen, D., Peterson, J. A., and Zillman, J. W., eds.** 1978. *Climatic Change and Variability: A Southern Perspective*. (Based on a conference at Monash University, Australia, December 7–12, 1975.) New York: Cambridge University Press.
33. **Environmental Protection Agency.** 2008. *Air Trends Through 2007*. www.epa.gov.
34. **Colin, M.** 2000. Is your office killing you? *BusinessWeek*, June 5, 114–124.
35. **Zummo, S. M., and Karol, M. H.** 1996. Indoor air pollution: Acute adverse health effects and host susceptibility. *Environmental Health* 58:25–29.
36. **Zimmerman, M. R.** 1985. Pathology in Alaskan mummies. *American Scientist* 73:20–25.
37. **Relis, P., and Dominski, A.** 1987. *Beyond the Crisis: Integrated Waste Management*. Santa Barbara, CA: Community Environmental Council.
38. **Relis, P., and Levenson, H.** 1998. *Discarding Solid Waste as We Know It: Managing Materials in the 21st Century.* Santa Barbara, CA: Community Environmental Council.
39. **Schneider, W. J.** 1970. *Hydraulic Implications of Solid-Waste Disposal.* U.S. Geological Survey Circular 601F.
40. **Turk, L. J.** 1970. Disposal of solid wastes—Acceptable practice or geological nightmare? In *Environmental Geology,* pp. 1–42. Washington, DC: American Geological Institute.
41. **Hughes, G. M.** 1972. Hydrologic considerations in the siting and design of landfills. *Environmental Geology Notes, No. 51.* Illinois State Geological Survey.
42. **Bergstrom, R. E.** 1968. Disposal of wastes: Scientific and administrative considerations. *Environmental Geology Notes, No. 20.* Illinois State Geological Survey.
43. **Cartwright, K., and Sherman, F. B.** 1969. Evaluating sanitary landfill sites in Illinois. *Environmental Geology Notes, No. 27.* Illinois State Geological Survey.
44. **Walker, W. H.** 1974. Monitoring toxic chemical pollution from land-disposal sites in humid regions. *Ground Water* 12:213–218.
45. **Environmental Protection Agency.** 1980. *Everybody's Problem: Hazardous Waste.* SW-826. Washington, DC: U.S. Government Printing Office.
46. **New York State Department of Environmental Conservation.** 1994. *Remedial Chronology: The Love Canal Hazardous Waste Site*. Albany, NY.
47. **Elliot, J.** 1980. Lessons from Love Canal. *Journal of the American Medical Association* 240:2033–2034, 2040.
48. **Kufs, C., and Twedwell, C.** 1980. Cleaning up hazardous landfills. *Geotimes* 25:18–19.
49. **Albeson, P. H.** 1983. Waste management. *Science* 220:1003.
50. **Return to Love Canal.** 1990. *Time* 135(22):27.
51. **Bedient, P. B., Rifai, H. S., and Newell, C. J.** 1994. *Ground Water Contamination*. Englewood Cliffs, NJ: Prentice Hall.
52. **Huddleston, R. L.** 1979. Solid-waste disposal: Landfarming. *Chemical Engineering* 86(5):119–124.
53. **Galley, J. E.** 1968. Economic and industrial potential of geologic basins and reservoir strata. In *Subsurface Disposal in Geologic Basins: A Study of Reservoir Strata,* ed. J. E. Galley, pp. 1–19. American Association of Petroleum Geologists Memoir 10.
54. **Committee of Geological Sciences.** 1972. *The Earth and Human Affairs*. San Francisco: Canfield Press.
55. **Piper, A. M.** 1970. *Disposal of Liquid Wastes by Injection Underground: Neither Myth nor Millennium.* U.S. Geological Survey Circular 631.
56. **Council on Environmental Quality.** 1979. *Environmental Quality*. Annual Report.
57. **Remy, M. H., Thomas, T. A., and Moose, J. G.** 1991. *Guide to the California Environmental Quality Act,* 5th ed. Point Arena, CA: Solano Press Books.
58. **Rohse, M.** 1987. *Land-Use Planning in Oregon*. Corvallis: Oregon State University Press.
59. **Curtin, D. J., Jr.** 1991. *California Land-Use and Planning-Law,* 11th ed. Point Arena, CA: Solano Press Books.
60. **William Spangle and Associates, F. Beach Leighton and Associates, and Baxter, McDonald and Company.** 1976. *Earth-Science Information in Land-Use Planning-Guidelines for Earth Scientists and Planners*. U.S. Geological Survey Circular 721.
61. **Murphy, E. F.** 1971. *Man and His Environment: Law*. New York: Harper & Row.
62. **Carter, L. J.** 1974. Con Edison: Endless Storm King dispute adds to its troubles. *Science* 184:1353–1358.
63. **Bacow, L. S., and Wheeler, M.** 1984. *Environmental Dispute Resolution*. New York: Plenum Press.
64. **Brown, L. R.** 2003. *Plan B: Rescuing a Planet Under Stress and a Civilization in Trouble.* New York: W. W. Norton & Co.
65. **Hawken, P., Lovins, A., and Lovins, L. H.** 1999. *Natural Capitalism*. Boston: Little, Brown and Co.
66. **Hubbard, B. M.** 1998. *Conscious Evolution*. Novato, CA: New World Library.

Index

A

B

D

H

I

Q

R

S

This page intentionally left blank

Volume

	in^3	ft^3	yd^3	m^3	qt	liter	barrel	gal. (U.S.)
1 in^3 =	1	—	—	—	—	0.02	—	—
1 ft^3 =	1,728	1	—	.0283	—	28.3	—	7.480
1 yd^3 =	—	27	1	0.76	—	—	—	—
1 m^3 =	61,020	35.315	1.307	1	—	1,000	—	—
1 quart (qt) =	—	—	—	—	1	0.95	—	0.25
1 liter (l) =	61.02	—	—	—	1.06	1	—	0.2642
1 barrel (oil) =	—	—	—	—	168	159.6	1	42
1 gallon (U.S.) =	231	0.13	—	—	4	3.785	0.02	1

Energy and Power

1 kilowatt-hour = 3,413 Btus = 860,421 calories
1 Btu = 0.000293 kilowatt-hour = 252 calories = 1,055 joule
1 watt = 3.413 Btu/hr = 14.34 calories/min
1 calorie = the amount of heat necessary to raise the temperature of 1 gram (1 cm^3) of water 1 degree Celsius
1 quadrillion Btu = (approximately) 1 exajoule
1 joule = 0.239 calorie = 2.778×10^{-7} kilowatt-hour

Mass and Weight

1 pound = 453.6 grams = 0.4536 kilogram = 16 ounces
1 gram = 0.0353 ounce = 0.0022 pound
1 short ton = 2,000 pounds = 907.2 kilograms
1 long ton = 2,240 pounds = 1,008 kilograms
1 metric ton = 2,205 pounds = 1,000 kilograms
1 kilogram = 2.205 pounds

Temperature

F is degrees Fahrenheit
C is degrees Celsius (centigrade)

$$F = \frac{9}{5}C + 32$$

Fahrenheit		Celsius
32	Freezing of H_2O (Atmospheric Pressure)	0
50		10
68		20
86		30
104		40
122		50
140		60
158		70
176		80
194		90
212	Boiling of H_2O (Atmospheric Pressure)	100

Other Conversion Factors

1 ft^3/sec = .0283 m^3/sec = 7.48 gal/sec = 28.32 liters/sec
1 acre-foot = 43,560 ft^3 = 1,233 m^3 = 325,829 gal
1 m^3/sec = 35.32 ft^3/sec
1 ft^3/sec for one day = 1.98 acre-feet
1 m/sec = 3.6 km/hr = 2.24 mi/hr
1 ft/sec = 0.682 mi/hr = 1.097 km/hr
1 billion gallons per day (bgd) = 3.785 million m^3 per day
1 atmosphere = 1.013×10^5 N/m^2 = approximately 1 bar
1 bar = approx. 10^5 N/m^2 = 10^5 pascal (Pa)

Strength of Common Rock Types

	Rock Type	Range of Compressive Strength (10^6 N/m^2)	Comments
Igneous	Granite	100 to 280	Finer-grained granites with few fractures are the strongest. Granite is generally suitable for most engineering purposes.
	Basalt	50 to greater than 280	Brecciated zones, open tubes, or fractures reduce the strength.
Metamorphic	Marble	100 to 125	Solutional openings and fractures weaken the rock.
	Gneiss	160 to 190	Generally suitable for most engineering purposes.
	Quartzite	150 to 600	Very strong rock.
Sedimentary	Shale	Less than 2 to 215	May be a very weak rock for engineering purposes; careful evaluation is necessary.
	Limestone	50 to 60	May have clay partings, solution openings, or fractures that weaken the rock.
	Sandstone	40 to 110	Strength varies with degree and type of cementing material, mineralogy, and nature and extent of fractures.

SOURCE: Data primarily from *Handbook of Tables for Applied Engineering Science,* ed. R. E. Bolz and G. L. Tuve (Cleveland, OH: CRC Press, 1973).

Commonly Used Multiples of 10

Prefix (Symbol)	Amount	Prefix (Symbol)	Amount
exa (E)	10^{18} (million trillion)	centi (c)	10^{-2} (one-hundredth)
peta (P)	10^{15} (thousand trillion)	milli (m)	10^{-3} (one-thousandth)
tera (T)	10^{12} (trillion)	micro (μ)	10^{-6} (one-millionth)
giga (G)	10^9 (billion)	nano (n)	10^{-9} (one-billionth)
mega (M)	10^6 (million)	pico (p)	10^{-12} (one-trillionth)
kilo (k)	10^3 (thousand)		

COMMON CONVERSION FACTORS

Length

1 yard = 3 ft, 1 fathom = 6 ft

	in	ft	mi	cm	m	km
1 inch (in) =	1	0.083	1.58×10^{-5}	2.54	0.0254	2.54×10^{-5}
1 foot (ft) =	12	1	1.89×10^{-4}	30.48	0.3048	
1 mile (mi) =	63,360	5,280	1	160,934	1,609	1.609
1 centimeter (cm) =	0.394	0.0328	6.2×10^{-6}	1	0.01	1.0×10^{-5}
1 meter (m) =	39.37	3.281	6.2×10^{-4}	100	1	0.001
1 kilometer (km) =	39,370	3,281	0.6214	100,000	1,000	1

Area

1 square mi = 640 acres, 1 acre = 43,650 ft^2 = 4046.86 m^2 = 0.4047 ha

1 ha = 10,000 m^2 = 2.471 acres

	in^2	ft^2	mi^2	cm^2	m^2	km^2
1 in^2 =	1		—	6.4516	—	—
1 ft^2 =	144	1	—	929	0.0929	—
1 mi^2 =	—	27,878,400	1	—	—	2.590
1 cm^2 =	0.155	—	—	1	—	—
1 m^2 =	1,550	10.764	—	10,000	1	—
1 km^2 =	—	—	0.3861	—	1,000,000	1

Volume

	in^3	ft^3	yd^3	m^3	qt	liter	barrel	gal. (U.S.)
1 in^3 =	1	—	—	—	—	0.02	—	—
1 ft^3 =	1,728	1	—	.0283	—	28.3	—	7.480
1 yd^3 =	—	27	1	0.76	—	—	—	—
1 m^3 =	61,020	35.315	1.307	1	—	1,000	—	—
1 quart (qt) =	—	—	—	—	1	0.95	—	0.25
1 liter (l) =	61.02	—	—	—	1.06	1	—	0.2642
1 barrel (oil) =	—	—	—	—	168	159.6	1	42
1 gallon (U.S.) =	231	0.13	—	—	4	3.785	0.02	1

Energy and Power

1 kilowatt-hour = 3,413 Btus = 860,421 calories
1 Btu = 0.000293 kilowatt-hour = 252 calories = 1,055 joule
1 watt = 3.413 Btu/hr = 14.34 calories/min
1 calorie = the amount of heat necessary to raise the temperature of 1 gram (1 cm^3) of water 1 degree Celsius
1 quadrillion Btu = (approximately) 1 exajoule
1 joule = 0.239 calorie = 2.778×10^{-7} kilowatt-hour

Mass and Weight

1 pound = 453.6 grams = 0.4536 kilogram = 16 ounces
1 gram = 0.0353 ounce = 0.0022 pound
1 short ton = 2,000 pounds = 907.2 kilograms
1 long ton = 2,240 pounds = 1,008 kilograms
1 metric ton = 2,205 pounds = 1,000 kilograms
1 kilogram = 2.205 pounds

Temperature

F is degrees Fahrenheit
C is degrees Celsius (centigrade)

$$F = \frac{9}{5}C + 32$$

Fahrenheit		Celsius
32	Freezing of H_2O (Atmospheric Pressure)	0
50	————	10
68	————	20
86	————	30
104	————	40
122	————	50
140	————	60
158	————	70
176	————	80
194	————	90
212	Boiling of H_2O (Atmospheric Pressure)	100

Other Conversion Factors

1 ft^3/sec = .0283 m^3/sec = 7.48 gal/sec = 28.32 liters/sec
1 acre-foot = 43,560 ft^3 = 1,233 m^3 = 325,829 gal
1 m^3/sec = 35.32 ft^3/sec
1 ft^3/sec for one day = 1.98 acre-feet
1 m/sec = 3.6 km/hr = 2.24 mi/hr
1 ft/sec = 0.682 mi/hr = 1.097 km/hr
1 billion gallons per day (bgd) = 3.785 million m^3 per day
1 atmosphere = 1.013×10^5 N/m^2 = approximately 1 bar
1 bar = approx. 10^5 N/m^2 = 10^5 pascal (Pa)

Strength of Common Rock Types

	Rock Type	**Range of Compressive Strength (10^6 N/m^2)**	**Comments**
Igneous	Granite	100 to 280	Finer-grained granites with few fractures are the strongest. Granite is generally suitable for most engineering purposes.
	Basalt	50 to greater than 280	Brecciated zones, open tubes, or fractures reduce the strength.
Metamorphic	Marble	100 to 125	Solutional openings and fractures weaken the rock.
	Gneiss	160 to 190	Generally suitable for most engineering purposes.
	Quartzite	150 to 600	Very strong rock.
Sedimentary	Shale	Less than 2 to 215	May be a very weak rock for engineering purposes; careful evaluation is necessary.
	Limestone	50 to 60	May have clay partings, solution openings, or fractures that weaken the rock.
	Sandstone	40 to 110	Strength varies with degree and type of cementing material, mineralogy, and nature and extent of fractures.

SOURCE: Data primarily from *Handbook of Tables for Applied Engineering Science*, ed. R. E. Bolz and G. L. Tuve (Cleveland, OH: CRC Press, 1973).

Commonly Used Multiples of 10

Prefix (Symbol)	**Amount**	**Prefix (Symbol)**	**Amount**
exa (E)	10^{18} (million trillion)	centi (c)	10^{-2} (one-hundredth)
peta (P)	10^{15} (thousand trillion)	milli (m)	10^{-3} (one-thousandth)
tera (T)	10^{12} (trillion)	micro (μ)	10^{-6} (one-millionth)
giga (G)	10^9 (billion)	nano (n)	10^{-9} (one-billionth)
mega (M)	10^6 (million)	pico (p)	10^{-12} (one-trillionth)
kilo (k)	10^3 (thousand)		

Geologic Time with Important Events

Era	Period	Epoch	Million Years before Present	Events: Life	Events: Earth	Million Years before Present	True Scale (Million Years before Present)
Cenozoic	Quaternary	Holocene	0.01	• Extinction event • Modern humans	Ice Age; Formation of Transverse Ranges, CA		Cenozoic
		Pleistocene	1.65	• Early humans		1.65	
	Tertiary	Pliocene	5.2		Formation of Andes Mountains		
		Miocene	23	• Grasses	Collision of India with Asia forming Himalayan Mountains and Tibetan Plateau		
		Oligocene	35	• Whales			
		Eocene	56	• Extinction event			
		Paleocene	65	• Mammals expand	Rocky Mountains form	65	
Mesozoic	Cretaceous		146	• Dinosaur extinction[1], extinction event • Flowering plants	Emplacement of Sierra Nevada Granites (Yosemite National Park)		Mesozoic
	Jurassic		208	• Birds	• Supercontinent Pangaea begins to break up		
	Triassic		245	• Mammals • Dinosaurs		245	
Paleozoic	Permian		290	• Extinction event • Reptiles	• Ice Age		Paleozoic
	Carboniferous		363	• Trees (coal swamps) • Extinction event			
	Devonian		417		Appalachian Mountains form		
	Silurian		443	• Land plants • Extinction event			
	Ordovician		495	• Fish			
	Cambrian		545	• Explosion of organisms with shells		545	
Precambrian				• Multicelled organisms	• Ice Age		Precambrian
			2500	• Free oxygen in atmosphere and ozone layer in stratosphere	• Ice Age		
			3500	• Primitive life (first fossils)			
			4000		• Oldest rocks		
			4600		• Age of Earth	4600	4600

[1] Some scientists believe that not all dinosaurs became extinct but that some dinosaurs evolved to birds.